

# Resolutions of homogeneous bundles on $\mathbf{P}^2$

Giorgio Ottaviani      Elena Rubei

## 1 Introduction

Homogeneous bundles on  $\mathbf{P}^2 = SL(3)/P$  can be described by representations of the parabolic subgroup  $P$ . In 1966 Ramanan proved that if  $\rho$  is an irreducible representation of  $P$  then the induced bundle  $E_\rho$  on  $\mathbf{P}^2$  is simple and even stable (see [Ram]). Since  $P$  is not a reductive group, there is a lot of indecomposable reducible representations of  $P$  and to classify homogeneous bundles on  $\mathbf{P}^2$  and among them the simple ones, the stable ones, etc. by means of the study of the representations of the parabolic subgroup  $P$  seems difficult.

In this paper our point of view is to consider the minimal free resolution of the bundle. Our aim is to classify homogeneous vector bundles on  $\mathbf{P}^2$  by means of their minimal resolutions. Precisely we observe that if  $E$  is a homogeneous vector bundle on  $\mathbf{P}^2 = \mathbf{P}(V)$  ( $V$  complex vector space of dimension 3) there exists a minimal free resolution of  $E$

$$0 \rightarrow \bigoplus_q \mathcal{O}(-q) \otimes_{\mathbf{C}} A_q \rightarrow \bigoplus_q \mathcal{O}(-q) \otimes_{\mathbf{C}} B_q \rightarrow E \rightarrow 0$$

with  $SL(V)$ -invariant maps ( $A_q$  and  $B_q$  are  $SL(V)$ -representations) and we characterize completely the representations that can occur as  $A_q$  and  $B_q$  and the maps  $A \rightarrow B$  that can occur ( $A := \bigoplus_q \mathcal{O}(-q) \otimes_{\mathbf{C}} A_q$ ,  $B = \bigoplus_q \mathcal{O}(-q) \otimes_{\mathbf{C}} B_q$ ). To state the theorem we need some notation.

**Notation 1** Let  $q, r \in \mathbf{N}$ ; for every  $\rho \geq p$ , let  $\varphi_{\rho,p}$  be a fixed  $SL(V)$ -invariant nonzero map  $S^{\rho,q,r}V \otimes \mathcal{O}_{\mathbf{P}(V)}(p) \rightarrow S^{\rho,q,r}V \otimes \mathcal{O}_{\mathbf{P}(V)}(\rho)$  (it is unique up to multiples) s.t.  $\varphi_{\rho,p} = \varphi_{\rho,p'} \circ \varphi_{p',p}$   $\forall \rho \geq p' \geq p$  (where  $S^{\rho,q,r}$  denotes the Schur functor associated to  $(p, q, r)$ , see §2).

Let  $\mathcal{P}, \mathcal{R} \subset \mathbf{N}$ ,  $c \in \mathbf{Z}$ ; for any  $SL(V)$ -invariant map

$$\gamma : \bigoplus_{p \in \mathcal{P}} A^p \otimes S^{\rho,q,r}V(c+p) \rightarrow \bigoplus_{\rho \in \mathcal{R}} B^\rho \otimes S^{\rho,q,r}V(c+\rho)$$

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**Address (of both authors):** Dipartimento di Matematica “U.Dini”, Viale Morgagni 67/A, c.a.p. 50134 Firenze, Italia. **E-mail addresses:** ottaviani@math.unifi.it, rubei@math.unifi.it

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( $A^p$  and  $B^\rho$  vector spaces) we define  $M(\gamma)$  to be the map

$$M(\gamma) : \bigoplus_{p \in \mathcal{P}} A^p \rightarrow \bigoplus_{\rho \in \mathcal{R}} B^\rho$$

s.t.  $\gamma_{\rho,p} = M(\gamma)_{\rho,p} \otimes \varphi_{\rho,p}$   $\forall \rho, p$  with  $\rho \geq p$  and  $M(\gamma)_{\rho,p} = 0$   $\forall \rho, p$  with  $\rho < p$ , where  $\gamma_{\rho,p} : A^p \otimes S^{p,q,r}V(c+p) \rightarrow B^\rho \otimes S^{\rho,q,r}V(c+\rho)$  and  $M(\gamma)_{\rho,p} : A^p \rightarrow B^\rho$  are the maps induced respectively by  $\gamma$  and  $M(\gamma)$  (by restricting and projecting).

**Theorem 2** *i) On  $\mathbf{P}^2 = \mathbf{P}(V)$  let  $A = \bigoplus_{p,q,i} A_i^{p,q} \otimes S^{p,q}V(i)$ ,  $B = \bigoplus_{p,q,i} B_i^{p,q} \otimes S^{p,q}V(i)$  with  $p, q, i$  varying in a finite subset of  $\mathbf{N}$ ,  $A_i^{p,q}$  and  $B_i^{p,q}$  finite dimensional vector spaces. Then  $A$  and  $B$  are the first two terms of a minimal free resolution of a homogeneous bundle on  $\mathbf{P}^2$  if and only if  $\forall c \in \mathbf{Z}, q, \tilde{p} \in \mathbf{N}$*

$$\dim(\bigoplus_{p \geq \tilde{p}} A_{c+p}^{p,q}) \leq \dim(\bigoplus_{\rho > \tilde{p}} B_{c+\rho}^{\rho,q})$$

*ii) Let*

$$A = \bigoplus_{p,q,r} A^{p,q,r} \otimes S^{p,q,r}V(p+q+r) \quad B = \bigoplus_{p,q,r} B^{p,q,r} \otimes S^{p,q,r}V(p+q+r)$$

*p, q, r varying in a finite subset of  $\mathbf{N}$ ,  $A^{p,q,r}$  and  $B^{p,q,r}$  finite dimensional vector spaces; let  $\alpha$  be an  $SL(V)$ -invariant map  $A \rightarrow B$ . Then there exists a homogeneous bundle  $E$  on  $\mathbf{P}^2$  s.t.*

$$0 \rightarrow A \xrightarrow{\alpha} B \rightarrow E \rightarrow 0$$

*is a minimal free resolution of  $E$  if and only if  $M(\alpha_{p,q,r}) : A^{p,q,r} \rightarrow B^{p,q,r}$  is zero  $\forall p, q, r$  and  $M(\alpha_{q,r}) : \bigoplus_p A^{p,q,r} \rightarrow \bigoplus_\rho B^{\rho,q,r}$  is injective  $\forall q, r$ , where  $\alpha_{p,q,r} : A^{p,q,r} \otimes S^{p,q,r}V(p) \rightarrow B^{p,q,r} \otimes S^{p,q,r}V(p)$  and  $\alpha_{q,r} : \bigoplus_p A^{p,q,r} \otimes S^{p,q,r}V(p) \rightarrow \bigoplus_\rho B^{\rho,q,r} \otimes S^{\rho,q,r}V(p)$  are the maps induced by  $\alpha$ .*

The above theorem allows us to parametrize the set of homogeneous bundles on  $\mathbf{P}^2$  by a set of sequences of injective matrices with a certain shape up to the action of invertible matrices with a certain shape. An interesting problem is to use this parametrization to study the related moduli spaces.

Then we begin to study which minimal free resolutions give simple or stable homogeneous bundles. We will consider the case  $A$  is irreducible; we call a homogeneous bundle *elementary* if it has minimal free resolution  $0 \rightarrow A \rightarrow B \rightarrow E \rightarrow 0$  with  $A$  irreducible; besides we say that a bundle  $E$  on  $\mathbf{P}^2$  is *regular* if the minimal free resolution is  $0 \rightarrow A \rightarrow B \rightarrow E \rightarrow 0$  with all the components of  $A$  with the same twist and all the components of  $B$  with the same twist.

First we study simplicity and stability of regular elementary homogeneous bundles. Fundamental tool are quivers and representations of quivers associated to homogeneous bundles introduced by Bondal and Kapranov in [B-K]. The quivers allow us to handle well and “to make explicit” the homogeneous subbundles of a homogeneous bundle  $E$  and Rohmfeld’s criterion (see [Rohm]) in this context is equivalent

to saying that  $E$  is semistable if and only if the slope of every subbundle associated to a subrepresentation of the quiver representation of  $E$  is less or equal than the slope of  $E$ .

The simplest regular elementary homogeneous bundles are the bundles  $E$  defined by the exact sequence

$$0 \rightarrow S^{p,q}V \otimes \mathcal{O}(-s) \xrightarrow{\varphi} S^{p+s,q}V \otimes \mathcal{O} \rightarrow E \rightarrow 0$$

for some  $p, q, s \in \mathbf{N}$ ,  $p \geq q$ ,  $\varphi$  an  $SL(V)$ -invariant nonzero map; we prove that such bundles are stable, see Theorem 36 (observe that Ramanan's theorem does not apply here). In the particular case  $p = q = 0$  the stability of  $E$  was already proved in [Ba].

Besides we prove

**Theorem 3** *A regular elementary homogeneous bundle  $E$  on  $\mathbf{P}^2$  is simple if and only if its minimal free resolution is of the following kind:*

$$0 \rightarrow S^{p,q}V \otimes \mathcal{O}(-s) \xrightarrow{\varphi} W \otimes \mathcal{O} \rightarrow E \rightarrow 0$$

where  $p, q, s \in \mathbf{N}$ ,  $p \geq q$ ,  $W$  is a nonzero  $SL(V)$ -submodule of  $S^{p,q}V \otimes S^sV$ , all the components of  $\varphi$  are nonzero  $SL(V)$ -invariant maps and we are in one of the following cases:

- i)  $p = 0$
- ii)  $p > 0$  and  $W \neq S^{p,q}V \otimes S^sV$ .

By using the above theorem and Theorem 47, which characterizes stability of the minimal free resolution of regular elementary homogeneous bundles when (with the above notation)  $s = 1$ , we find infinite examples of unstable simple homogeneous bundles.

Finally we state a criterion, generalizing Theorem 3, to say when an elementary (not necessarily regular) homogeneous bundle is simple by means of its minimal free resolution, see Theorem 48.

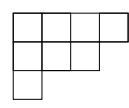
The sketch of the paper is the following: in §2 we recall some basic facts on representation theory; in §3 we characterize the resolutions of homogeneous bundles on  $\mathbf{P}^2$ : in this section we prove Theorem 9, which contains Theorem 2; in §4 we recall the theory of quivers; in §5 we prove some lemmas by using quivers and we fix some notation; in §6 we study stability and simplicity of elementary homogeneous bundles.

## 2 Notation and preliminaries

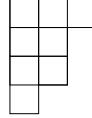
We recall some facts on representation theory (see for instance [F-H]).

Let  $d$  be a natural number and let  $\lambda = (\lambda_1, \dots, \lambda_k)$  be a partition of  $d$  with  $\lambda_1 \geq \dots \geq \lambda_k$ .

We can associate to  $\lambda$  a **Young diagram** with  $\lambda_i$  boxes in the  $i$ -th row, the rows lined up on the left. The conjugate partition  $\lambda'$  is the partition of  $d$  whose Young diagram is obtained from the Young diagram of  $\lambda$  interchanging rows and columns. A **tableau** with entries in  $\{1, \dots, n\}$  on the Young diagram of a partition  $\lambda = (\lambda_1, \dots, \lambda_k)$  of  $d$  is a numbering of the boxes by the integers  $1, \dots, n$ , allowing repetitions (we say also that it is a tableau on  $\lambda$ ).



Young diagram of (4,3,1)



Young diagram of (3,2,2,1),  
conjugate of (4,3,1)

2	3	6	1
8	5	4	
1			

A tableau on (4,3,1)

**Definition 4** Let  $V$  be a complex vector space of dimension  $n$ . Let  $d \in \mathbf{N}$  and let  $\lambda = (\lambda_1, \dots, \lambda_k)$  be a partition of  $d$ , with  $\lambda_1 \geq \dots \geq \lambda_k$ . Number the boxes of the Young diagram of  $\lambda$  with the numbers  $1, \dots, d$  from left to right beginning from the top row. Let  $\Sigma_d$  be the group of permutations on  $d$  elements; let  $R$  be the subgroup of  $\Sigma_d$  given by the permutations preserving the rows and let  $C$  be the subgroup of  $\Sigma_d$  given by the permutations preserving the columns.

We define

$$S^\lambda V := \text{Im} \left( \sum_{a \in C, s \in R} \text{sign}(a)s \circ a : \otimes^d V \rightarrow \otimes^d V \right)$$

The  $S^\lambda V$  are called **Schur representations**.

The  $S^\lambda V$  are irreducible  $SL(V)$ -representations and it is well-known that all the irreducible  $SL(V)$ -representations are of this form.

**Notation 5** • Let  $V$  be a complex vector space and let  $\{v_j\}_{1, \dots, n}$  be a basis of  $V$ . Let  $d \in \mathbf{N}$  and  $\lambda = (\lambda_1, \dots, \lambda_k)$  be a partition of  $d$  with  $\lambda_1 \geq \dots \geq \lambda_k$ . Let  $\mu$  be the conjugate partition. Let  $\mathcal{G}_\lambda$  be the free abelian group generated by the tableaux on  $\lambda$  with entries in  $\{1, \dots, n\}$  and let  $\mathcal{T}_\lambda = \mathcal{G}_\lambda \otimes_{\mathbf{Z}} \mathbf{C}$ .

• Let  $t$  be the map associating to a tableau  $T$  on  $\lambda$  with entries in  $\{1, \dots, n\}$  the following element of  $V^{\otimes d}$ :

$$v_{T_1^1} \otimes \dots \otimes v_{T_{\lambda_1}^1} \otimes \dots \otimes v_{T_1^k} \otimes \dots \otimes v_{T_{\lambda_k}^k}$$

where  $(T_1^j \dots T_{\lambda_j}^j)$  is the  $j$ -th row of  $T$ .

• We define  $\text{ant} : \mathcal{T}_\lambda \rightarrow \mathcal{T}_\lambda$  to be the linear map s.t. for every tableau  $T$  on  $\lambda$

$$\text{ant}(T) = \sum_{(\sigma_1, \dots, \sigma_{\lambda_1}) \in \Sigma_{\mu_1} \times \dots \times \Sigma_{\mu_{\lambda_1}}} \text{sign}(\sigma_1) \dots \text{sign}(\sigma_{\lambda_1}) T^{\sigma_1, \dots, \sigma_{\lambda_1}}$$

where  $T^{\sigma_1, \dots, \sigma_{\lambda_1}}$  is the tableau obtained from  $T$  permuting the elements of the  $j$ -th column with  $\sigma_j \forall j$ . For instance

$$\begin{array}{|c|c|c|} \hline 1 & 2 & 3 \\ \hline 4 & 5 & \\ \hline \end{array} \xrightarrow{\text{ant}} \begin{array}{|c|c|c|} \hline 1 & 2 & 3 \\ \hline 4 & 5 & \\ \hline \end{array} - \begin{array}{|c|c|c|} \hline 4 & 2 & 3 \\ \hline 1 & 5 & \\ \hline \end{array} - \begin{array}{|c|c|c|} \hline 1 & 5 & 3 \\ \hline 4 & 2 & \\ \hline \end{array} + \begin{array}{|c|c|c|} \hline 4 & 5 & 3 \\ \hline 1 & 2 & \\ \hline \end{array}$$

- Analogously we define  $\text{sim} : \mathcal{T}_\lambda \rightarrow \mathcal{T}_\lambda$  to be the linear map s.t. for every tableau  $T$  on  $\lambda$

$$\text{sim}(T) = \sum_{(\sigma_1, \dots, \sigma_{\mu_1}) \in \Sigma_{\lambda_1} \times \dots \times \Sigma_{\lambda_{\mu_1}}} T_{\sigma_1, \dots, \sigma_{\mu_1}}$$

where  $T_{\sigma_1, \dots, \sigma_{\mu_1}}$  is the tableau obtained from  $T$  permuting the elements of the  $j$ -th row with  $\sigma_j \forall j$ . For instance

$$\begin{array}{|c|c|} \hline 1 & 2 \\ \hline 4 & 3 \\ \hline \end{array} \xrightarrow{\text{sim}} \begin{array}{|c|c|} \hline 1 & 2 \\ \hline 4 & 3 \\ \hline \end{array} + \begin{array}{|c|c|} \hline 2 & 1 \\ \hline 4 & 3 \\ \hline \end{array} + \begin{array}{|c|c|} \hline 1 & 2 \\ \hline 3 & 4 \\ \hline \end{array} + \begin{array}{|c|c|} \hline 2 & 1 \\ \hline 3 & 4 \\ \hline \end{array}$$

- We call  $\text{ord}$  the linear map associating to a tableau  $T$  the tableau obtained from  $T$  ordering the entries of every row in nondecreasing way.

Observe that  $\text{ord} \circ \text{sim} = \lambda_1! \dots \lambda_k! \text{ord}$  and  $\text{sim} \circ \text{ord} = \text{sim}$ .

- Let  $\mathcal{S} = t \circ \text{sim} \circ \text{ant}$ .

Obviously the space  $S^\lambda V$  can be described as the image of  $\mathcal{S} : \mathcal{T}_\lambda \rightarrow V^{\otimes d}$ .

We recall that **Pieri's formula** says that, if  $\lambda = (\lambda_1, \lambda_2, \dots)$  is a partition of a natural number  $d$  with  $\lambda_1 \geq \lambda_2 \geq \dots$  and  $t$  is a natural number, then

$$S^\lambda V \otimes S^t V = \bigoplus_{\nu} S^\nu V$$

as  $SL(V)$ -representations, where the sum is performed on all the partitions  $\nu = (\nu_1, \dots)$  with  $\nu_1 \geq \nu_2 \geq \dots$  of  $d + t$  whose Young diagrams are obtained from the Young diagram of  $\lambda$  adding  $t$  boxes not two in the same column.

Finally we observe that if  $V$  is a complex vector space of dimension  $n$  then  $S^{(\lambda_1, \dots, \lambda_{n-1})} V$  is isomorphic to  $S^{(\lambda_1+r, \dots, \lambda_{n-1}+r, r)} V$  for all  $r$  as  $SL(V)$ -representation. Besides  $(S^{(\lambda_1, \dots, \lambda_n)} V)^\vee$  is isomorphic as  $SL(V)$ -representation to  $S^{(\lambda_1 - \lambda_n, \dots, \lambda_1 - \lambda_2)} V$ . Moreover  $(S^\lambda V)^\vee \simeq S^\lambda V^\vee$ .

**Notation 6** • In all the paper  $V$  will be a complex vector space of dimension 3 if not otherwise specified.

- If  $E$  is a vector bundle on  $\mathbf{P}(V)$  then  $\mu(E)$  will denote the slope of  $E$ , i.e. the first Chern class divided by the rank.

### 3 Resolutions of homogeneous vector bundles

The aim of this section is to characterize the minimal free resolutions of the homogeneous bundles on  $\mathbf{P}^2$ .

**Lemma 7** *Let  $E$  be a homogeneous vector bundle on  $\mathbf{P}^2 = \mathbf{P}(V)$ . By Horrocks' theorem [Hor] the bundle  $E$  has a minimal free resolution*

$$0 \rightarrow \bigoplus_q \mathcal{O}(-q) \otimes_{\mathbf{C}} A_q \rightarrow \bigoplus_q \mathcal{O}(-q) \otimes_{\mathbf{C}} B_q \xrightarrow{\psi} E \rightarrow 0$$

( $A_q, B_q$   $\mathbf{C}$ -vector spaces). Since  $E$  is homogeneous we can suppose the maps are  $SL(V)$ -invariant maps ( $A_q$  and  $B_q$  are  $SL(V)$ -representations).

*Proof.* (See also [Ka]). Let  $M := \bigoplus_k H^0(E(k))$  and  $S = \bigoplus_k \text{Sym}^k V^\vee$ . Let  $m_i \in M$   $i = 1, \dots, k$  s.t. no one of them can be written as linear combination with coefficient in  $S$  of elements of the  $SL(V)$ -orbits of the others and s.t.  $\cup_{g \in SL(V), i=1, \dots, k} g(m_i)$  generates  $M$  on  $S$ . Let  $q_i = \deg(m_i)$ . Let  $B_i := \langle \cup_{g \in SL(V)} g(m_i) \rangle_{\mathbf{C}}$  (finite dimensional  $SL(V)$ -representations). Let  $P = \bigoplus_i B_i \otimes_{\mathbf{C}} S(-q_i)$  and  $\varphi : P \rightarrow M$  be the  $SL(V)$ -invariant map given by multiplication. Let  $\psi : B \rightarrow E$  be the sheafification of  $\varphi : P \rightarrow M$ . Thus  $B = \bigoplus_i B_i \otimes \mathcal{O}(-q_i)$ . Let  $A = \text{Ker}(\psi)$ ; it is a homogeneous vector bundle; we have  $H^1(A(t)) = 0 \ \forall t \in \mathbf{Z}$ , because  $H^0(B(t)) \rightarrow H^0(E(t))$  is surjective  $\forall t$  and  $H^1(B(t)) = 0 \ \forall t$ , hence by Horrocks' criterion  $A$  splits.  $\square$

**Remark 8** a) If  $U, W, V$  are three vector spaces then on  $P(V)$  we have  $\text{Hom}(U \otimes \mathcal{O}(-s), W) = \text{Hom}(U \otimes S^s V, W)$  (the isomorphism can be given by  $H^0(\cdot^\vee)^\vee$ ).

b) Let  $V$  be a vector space. For any  $\lambda, \mu$  partitions,  $s \in \mathbf{N}$ , up to multiples there is a unique  $SL(V)$ -invariant map

$$S^\lambda V \otimes \mathcal{O}(-s) \rightarrow S^\mu V \otimes \mathcal{O}$$

by Pieri's formula, Schur's lemma and part a of the remark.

Theorem 9, which implies Theorem 2, is the aim of this section. It allows us to classify all homogeneous vector bundles on  $\mathbf{P}^2$ ; in fact it characterizes their minimal free resolutions.

Precisely part i allows us to say which  $A$  and  $B$  can occur in a minimal free resolution  $0 \rightarrow A \rightarrow B \rightarrow E \rightarrow 0$  of a homogeneous vector bundle  $E$  on  $\mathbf{P}^2$ ; first we investigate when, given  $A$  and  $B$  direct sums of bundles of the kind  $S^{p,q} V(-i)$ , there exists an injective  $SL(V)$ -invariant map  $A \rightarrow B$ ; roughly speaking this is true if and only if for every  $SL(V)$ -irreducible subbundle  $S = S^{p,q} V(i)$  of  $A$  there exists a subbundle  $M(S)$  of  $B$  of the kind  $S^{p+s,q} V(i+s)$  for some  $s \in \mathbf{N}$  and we can choose  $M(S)$  in such way that the map  $S \mapsto M(S)$  is injective. A crucial point of the proof is the fact that an  $SL(V)$ -invariant map  $S^{p,q} V \rightarrow S^{p+s_1, q+s_2, s_3} V(s_1 + s_2 + s_3)$  is injective

if and only if  $s_2 = s_3 = 0$  and the intersection of the kernels of the ones of such maps with  $s_2 + s_3 > 0$  is nonzero.

Part *ii* allows us to say which maps  $A \rightarrow B$  can occur in a minimal free resolution  $0 \rightarrow A \rightarrow B \rightarrow E \rightarrow 0$  of a homogeneous bundle  $E$ ; first we study when an  $SL(V)$ -invariant map  $\alpha : A \rightarrow B$  is injective ( $A$  and  $B$  direct sums of bundles of the kind  $S^{p,q,r}V(-i)$ ). We remark that, if  $\alpha : A \rightarrow B$  is an  $SL(V)$ -invariant map, we can suppose that the sum  $p+q+r-i$  is constant for  $S^{p,q,r}V(i)$  varying among all  $SL(V)$ -irreducible subbundles of  $A$  or  $B$  (by using the isomorphism  $S^{p,q}V \simeq S^{p+u,q+u,u}V \forall u \in \mathbf{N}$ ).

In the sequel we will use Notation 1.

**Theorem 9** *i) On  $\mathbf{P}^2 = \mathbf{P}(V)$  let  $A = \bigoplus_{p,q,i} A_i^{p,q} \otimes S^{p,q}V(i)$ ,  $B = \bigoplus_{p,q,i} B_i^{p,q} \otimes S^{p,q}V(i)$  with  $p, q, i$  varying in a finite subset of  $\mathbf{N}$ ,  $A_i^{p,q}$  and  $B_i^{p,q}$  finite dimensional vector spaces. There exists an injective  $SL(V)$ -invariant map  $A \rightarrow B$  if and only if  $\forall c \in \mathbf{Z}, q, \tilde{p} \in \mathbf{N}$*

$$\dim(\bigoplus_{p \geq \tilde{p}} A_{c+p}^{p,q}) \leq \dim(\bigoplus_{\rho \geq \tilde{p}} B_{c+\rho}^{\rho,q}) \quad (1)$$

*i') Besides  $A$  and  $B$  are the first two terms of a minimal free resolution of a homogeneous bundle on  $\mathbf{P}^2$  if and only if  $\forall c \in \mathbf{Z}, q, \tilde{p} \in \mathbf{N}$*

$$\dim(\bigoplus_{p \geq \tilde{p}} A_{c+p}^{p,q}) \leq \dim(\bigoplus_{\rho > \tilde{p}} B_{c+\rho}^{\rho,q}) \quad (2)$$

*ii) Let*

$$A = \bigoplus_{p,q,r} A^{p,q,r} \otimes S^{p,q,r}V(p+q+r) \quad B = \bigoplus_{p,q,r} B^{p,q,r} \otimes S^{p,q,r}V(p+q+r)$$

*p, q, r varying in a finite subset of  $\mathbf{N}$ ,  $A^{p,q,r}$  and  $B^{p,q,r}$  finite dimensional vector spaces; let  $\alpha$  be an  $SL(V)$ -invariant map  $A \rightarrow B$ ;  $\alpha$  is injective if and only if  $\forall q, r$  the induced map*

$$\alpha_{q,r} : \bigoplus_p A^{p,q,r} \otimes S^{p,q,r}V(p+q+r) \rightarrow \bigoplus_\rho B^{\rho,q,r} \otimes S^{\rho,q,r}V(\rho+q+r)$$

*is injective and (by Lemma 13) this is true if and only if  $M(\alpha_{q,r}) : \bigoplus_p A^{p,q,r} \rightarrow \bigoplus_\rho B^{\rho,q,r}$  is injective.*

*Besides obviously there exists a homogeneous bundle  $E$  on  $\mathbf{P}^2$  s.t.*

$$0 \rightarrow A \xrightarrow{\alpha} B \rightarrow E \rightarrow 0$$

*is the minimal free resolution of  $E$  if and only if  $M(\alpha_{q,r}) : \bigoplus_p A^{p,q,r} \rightarrow \bigoplus_\rho B^{\rho,q,r}$  is injective  $\forall q, r$  and  $M(\alpha_{p,q,r}) : A^{p,q,r} \rightarrow B^{p,q,r}$  is zero  $\forall p, q, r$ .*

To prove Theorem 9 we need some lemmas.

**Lemma 10** Let  $V$  be a complex vector space of dimension  $n$ . Let  $\lambda_1, \dots, \lambda_{n-1}, s \in \mathbf{N}$  with  $\lambda_1 \geq \dots \geq \lambda_{n-1}$  and

$$\pi : S^{\lambda_1, \dots, \lambda_{n-1}} V \otimes S^s V \rightarrow S^{\lambda_1+s, \lambda_2, \dots, \lambda_{n-1}} V$$

be an  $SL(V)$ -invariant nonzero map. Then (up to multiples)  $\pi$  can be described in the following way: let  $T$  be a tableau on  $(\lambda_1, \dots, \lambda_{n-1})$  and let  $R$  be a tableau on  $(s)$ ; then

$$\pi(\mathcal{S}(T) \otimes \mathcal{S}(R)) = \mathcal{S}(TR)$$

where  $TR$  is the tableau obtained from  $T$  adding  $R$  at the end of its first row and  $\mathcal{S}$  is defined in Notation 5. In particular on  $\mathbf{P}^{n-1} = \mathbf{P}(V)$  any  $SL(V)$ -invariant nonzero map

$$S^{\lambda_1, \dots, \lambda_{n-1}} V(-s) \rightarrow S^{\lambda_1+s, \lambda_2, \dots, \lambda_{n-1}} V$$

is injective.

*Proof.* Let  $\varphi : S^{\lambda_1, \dots, \lambda_{n-1}} V \otimes S^s V \rightarrow S^{\lambda_1+s, \lambda_2, \dots, \lambda_{n-1}} V$  be the linear map s.t.  $\varphi(\mathcal{S}(T) \otimes \mathcal{S}(R)) = \mathcal{S}(TR)$   $\forall T$  tableau on  $(\lambda_1, \dots, \lambda_{n-1})$  and  $\forall R$  tableau on  $(s)$ ; it is sufficient to prove that  $\varphi$  is well defined,  $SL(V)$ -invariant and nonzero.

To show that it is well defined it is sufficient to show that, if  $T, T' \in \mathcal{T}_{(\lambda_1, \dots, \lambda_{n-1})}$  s.t.  $\mathcal{S}(T) = \mathcal{S}(T')$  and  $R, R' \in \mathcal{T}_{(s)}$  s.t.  $\mathcal{S}(R) = \mathcal{S}(R')$ , then  $\mathcal{S}(TR) = \mathcal{S}(T'R')$  (with the obvious definition of  $TR$ ). Observe that

$$\mathcal{S}(TR) = \mathcal{S}(T'R') \Leftrightarrow \text{ord}(\text{ant}(TR)) = \text{ord}(\text{ant}(T'R')) \Leftrightarrow \text{ord}(\text{ant}(T)R) = \text{ord}(\text{ant}(T')R')$$

and the last equality follows from the fact that  $\text{ord}(\text{ant}(T)) = \text{ord}(\text{ant}(T'))$  because  $\text{sim}(\text{ant}(T)) = \text{sim}(\text{ant}(T'))$  and  $\text{ord}(R) = \text{ord}(R')$  because  $\text{sim}(R) = \text{sim}(R')$ .

Besides obviously the map  $\mathcal{S}(T) \otimes \mathcal{S}(R) \mapsto \mathcal{S}(TR)$  is  $SL(V)$ -invariant and nonzero. Thus, up to multiples, it is the map  $\pi$ .

This implies the injectivity of any  $SL(V)$ -invariant nonzero map  $S^{\lambda_1, \dots, \lambda_{n-1}} V(-s) \rightarrow S^{\lambda_1+s, \lambda_2, \dots, \lambda_{n-1}} V$ ; in fact the induced map on the fibre on  $[0 : \dots : 0 : 1]$  is

$$\mathcal{S}(T) \mapsto \mathcal{S}(T[n \dots n])$$

$\forall T \in \mathcal{T}_{(\lambda_1, \dots, \lambda_{n-1})}$  and if  $\mathcal{S}(T[n \dots n]) = 0$ , then  $\text{ord} \circ \text{sim} \circ \text{ant}(T[n \dots n]) = 0$ ; thus  $\text{ord} \circ \text{ant}(T[n \dots n]) = 0$ , but  $\text{ord} \circ \text{ant}(T[n \dots n]) = (\text{ord} \circ \text{ant}(T))[n \dots n]$ , hence  $\text{ord} \circ \text{ant}(T) = 0$ , i.e.  $\mathcal{S}(T) = 0$ .  $\square$

The injectivity statement of Lemma 10 (probably well known) will be obvious by the theory of quivers, precisely it will follow from Lemma 24, but we wanted to show the above proof because it is more elementary and intuitive.

**Lemma 11** Let  $\mathbf{P}^{n-1} = \mathbf{P}(V)$ . For every  $\lambda_1, \dots, \lambda_n \in \mathbf{N}$ ,  $t \in \mathbf{Z}$  with  $\lambda_1 \geq \dots \geq \lambda_n$ ,  $\exists y = y_{\lambda_1, \dots, \lambda_n}^t \in S^{\lambda_1, \dots, \lambda_n} V(t)$ ,  $y \neq 0$  s.t.  $\varphi(y) = 0$  for every  $SL(V)$ -invariant map

$$\varphi : S^{\lambda_1, \dots, \lambda_n} V(t) \rightarrow S^{\lambda_1+s_1, \dots, \lambda_n+s_n} V(t+s_1 + \dots + s_n)$$

$\forall s_1, \dots, s_n \in \mathbf{N}$  s.t.  $s_2 + \dots + s_n > 0$ .

*Proof.* It is sufficient to prove the statement when  $t = 0$ . It is sufficient to take as  $y$  a nonzero element of the image of an  $SL(V)$ -invariant nonzero map

$$\psi : S^{\lambda_2, \dots, \lambda_n} V(-\lambda_1) \rightarrow S^{\lambda_1, \dots, \lambda_n} V$$

(such a map exists because, by Pieri's formula,  $S^{\lambda_1, \dots, \lambda_n} V$  is a summand of  $S^{\lambda_2, \dots, \lambda_n} V \otimes S^{\lambda_1} V$ , thus we can take the map induced by the projection; besides an  $SL(V)$ -invariant map

$$S^{\lambda_2, \dots, \lambda_n} V(-\lambda_1 - s_1 - \dots - s_n) \rightarrow S^{\lambda_1 + s_1, \dots, \lambda_n + s_n} V$$

is zero  $\forall s_1, \dots, s_n$  with  $s_2 + \dots + s_n > 0$ , because by Pieri's formula the induced map (i.e.  $H^0(\cdot \vee)^V$ )  $S^{\lambda_2, \dots, \lambda_n} V \otimes S^{\lambda_1 + s_1 + \dots + s_n} V \rightarrow S^{\lambda_1 + s_1, \dots, \lambda_n + s_n} V$  is zero, thus  $\varphi \circ \psi = 0$   $\forall \varphi$  as in the statement and then  $\varphi(y) = 0$ .  $\square$

**Remark 12** Let  $W$  be a finite dimensional  $\mathbf{C}$ -vector space and  $v_1, \dots, v_k \in W$  not all zero. Let  $B$  be a matrix with  $k$  columns s.t.  $\sum_{j=1, \dots, k} B_{i,j} v_j = 0 \forall i$  (i.e. the coefficients of every row of  $B$  are the coefficients of a linear relation among the  $v_j$ ). Then  $B : \mathbf{C}^k \rightarrow \mathbf{C}^s$  (where  $s$  is the number of the rows of  $B$ ) is not injective.

**Lemma 13** Fix  $q, r \in \mathbf{N}$  with  $q \geq r$  and let  $\mathcal{P}, \mathcal{R}$  be finite subsets of  $\{p \in \mathbf{N} \mid p \geq q\}$ . A map

$$\alpha : \bigoplus_{p \in \mathcal{P}} A^p \otimes S^{p, q, r} V(p) \rightarrow \bigoplus_{\rho \in \mathcal{R}} B^\rho \otimes S^{\rho, q, r} V(\rho)$$

( $A^p, B^\rho$  nonzero finite-dimensional vector spaces) is injective if and only if  $M(\alpha)$  is injective.

*Proof.* Let  $\underline{p} = \min \mathcal{P}$  and  $\bar{p} = \max \mathcal{P}$ . Let

$$\psi = \bigoplus_{p \in \mathcal{P}} I_{A^p} \otimes \varphi_{p, \underline{p}} : (\bigoplus_{p \in \mathcal{P}, p \geq \underline{p}} A^p) \otimes S^{\underline{p}, q, r} V(\underline{p}) \rightarrow \bigoplus_{p \in \mathcal{P}} A^p \otimes S^{p, q, r} V(p)$$

The map  $\psi$  is injective by Lemma 10. We have

$$\alpha \circ \psi = (\bigoplus_{\rho \in \mathcal{R}, \rho \geq \underline{p}} I_{B^\rho} \otimes \varphi_{\rho, \underline{p}}) \circ (M(\alpha) \otimes I_{S^{\underline{p}, q, r} V(\underline{p})}) \quad (3)$$

Suppose  $\alpha$  is injective. Since  $\psi$  is injective,  $\alpha \circ \psi$  is injective. Thus, by (3),  $M(\alpha)$  is injective.

Suppose now  $M(\alpha)$  is injective. Let  $x \in \mathbf{P}^2$ . Let  $\alpha^x$  be the map induced on the fibres on  $x$  by  $\alpha$  and for any bundle  $E$ ,  $E^x$  will denote the fibre on  $x$ .

Let  $\mathcal{P} = \{p_1, \dots, p_n\}$ . Let  $v = (v_1^1, \dots, v_{a_1}^1, \dots, \dots, v_1^n, \dots, v_{a_n}^n) \in \text{Ker}(\alpha^x)$  where  $a_i = \dim A^{p_i}$  and  $v_j^i \in S^{p_i, q, r} V(p_i)^x$ . We want to show  $v = 0$ .

We can see every  $v_j^i$  in  $S^{\bar{p}, q, r}(\bar{p})^x$  (by  $\varphi_{\bar{p}, p_i}$ , which is an injection); (after fixing bases and seeing  $M(\alpha)$  as a matrix) the coefficients of the rows of  $M(\alpha)$  are the coefficients of linear relations among the  $v_j^i$  seen in  $S^{\bar{p}, q, r}(\bar{p})^x$ , since  $\alpha^x(v) = 0$ . Thus, since  $M(\alpha)$  is injective, by Remark 12, the  $v_j^i$  must be all zero, i.e.  $v = 0$ .  $\square$

*Proof of Theorem 9.* *i)* Let  $\alpha : A \rightarrow B$  be an  $SL(V)$ -invariant injective map. For any  $c, q, \tilde{p}$ , let

$$\alpha_{c,q,\geq \tilde{p}} : \bigoplus_{p \geq \tilde{p}} A_{c+p}^{p,q} \otimes S^{p,q} V(c+p) \rightarrow \bigoplus_{\rho \geq \tilde{p}} B_{c+\rho}^{\rho,q} \otimes S^{\rho,q} V(c+\rho)$$

the map induced by  $\alpha$ , and let

$$\psi_{\tilde{p}} = \bigoplus_{p \geq \tilde{p}} I_{A_{c+p}^{p,q}} \otimes \varphi_{p,\tilde{p}}(c) : (\bigoplus_{p \geq \tilde{p}} A_{c+p}^{p,q}) \otimes S^{\tilde{p},q} V(c+\tilde{p}) \rightarrow \bigoplus_{p \geq \tilde{p}} A_{c+p}^{p,q} \otimes S^{p,q} V(c+p)$$

The map  $\psi_{\tilde{p}}$  is injective by Lemma 10. We can write

$$\alpha_{c,q,\geq \tilde{p}} \circ \psi_{\tilde{p}} = (\bigoplus_{\rho \geq \tilde{p}} I_{B_{c+\rho}^{\rho,q}} \otimes \varphi_{\rho,\tilde{p}}) \circ (M(\alpha_{c,q,\geq \tilde{p}}) \otimes I_{S^{\tilde{p},q} V(c+\tilde{p})}) \quad (4)$$

Let  $v \in \text{Ker } M(\alpha_{c,q,\geq \tilde{p}})$ . If  $v \neq 0$  then  $\psi_{\tilde{p}}(v \otimes y_{\tilde{p},q}^{c+\tilde{p}})$  (see Lemma 11 for the definition of  $y_{\tilde{p},q}^{c+\tilde{p}}$ ) is nonzero (since  $\psi_{\tilde{p}}$  is injective) and it is in  $\text{Ker}(\alpha)$  (in fact it is in  $\text{Ker}(\alpha_{c,q,\geq \tilde{p}})$  by (4) and thus in  $\text{Ker}(\alpha)$  by the definition of  $y_{\tilde{p},q}^{c+\tilde{p}}$ ). Since  $\alpha$  is injective we get a contradiction, thus  $v = 0$ . Thus  $M(\alpha_{c,q,\geq \tilde{p}})$  is injective. Then (1) holds.

Suppose now (1) holds. Since

$$A = \bigoplus_{c,q} (\bigoplus_p A_{c+p}^{p,q} \otimes S^{p,q} V(c+p)) \quad B = \bigoplus_{c,q} (\bigoplus_{\rho} B_{c+\rho}^{\rho,q} \otimes S^{\rho,q} V(c+\rho)),$$

to find an injective map  $\alpha : A \rightarrow B$  it is sufficient to find  $\forall c, q$  an injective map

$$\alpha_{c,q} : \bigoplus_p A_{c+p}^{p,q} \otimes S^{p,q} V(c+p) \rightarrow \bigoplus_{\rho} B_{c+\rho}^{\rho,q} \otimes S^{\rho,q} V(c+\rho)$$

Order  $p$  and  $\rho$  in decreasing way, fix a basis of  $A_{c+p}^{p,q} \forall p$  and let  $\alpha_{c,q}$  be the map s.t.:

$$M(\alpha_{c,q}) = \begin{pmatrix} I \\ 0 \end{pmatrix}$$

Observe that, since  $p$  and  $\rho$  are ordered in decreasing way and  $\dim(\bigoplus_{p \geq \tilde{p}} A_{c+p}^{p,q}) \leq \dim(\bigoplus_{\rho \geq \tilde{p}} B_{c+\rho}^{\rho,q})$ , then the entries equal to 1 are “where  $\rho \geq p$ ”.

*i')* First observe that an  $SL(V)$ -invariant injective map  $\alpha : A \rightarrow B$  is s.t.  $0 \rightarrow A \xrightarrow{\alpha} B \rightarrow \text{coker } \alpha \rightarrow 0$  is a minimal free resolution if and only if the maps induced by  $\alpha$

$$\alpha_{p,q,i} : A_i^{p,q} \otimes S^{p,q} V(i) \rightarrow B_i^{\rho,q} \otimes S^{\rho,q} V(i)$$

are zero.

Let  $0 \rightarrow A \xrightarrow{\alpha} B \rightarrow \text{coker } \alpha \rightarrow 0$  be a minimal free resolution with  $\alpha$   $SL(V)$ -invariant injective map. For any  $c, q, \tilde{p}$ , let

$$\alpha_{c,q,>\tilde{p},\geq \tilde{p}} : \bigoplus_{p \geq \tilde{p}} A_{c+p}^{p,q} \otimes S^{p,q} V(c+p) \rightarrow \bigoplus_{\rho > \tilde{p}} B_{c+\rho}^{\rho,q} \otimes S^{\rho,q} V(c+\rho)$$

the map induced by  $\alpha$ .

We can prove that  $M(\alpha_{c,q,>\tilde{p},\geq\tilde{p}})$  is injective as in the implication  $\Rightarrow$  of *i*, i.e. by considering  $\alpha_{c,q,>\tilde{p},\geq\tilde{p}} \circ \psi_{\tilde{p}}$  with  $\psi_{\tilde{p}}$  as above (to see  $\psi_{\tilde{p}}(v \otimes y_{\tilde{p},q}^{c+\tilde{p}})$  is in  $\text{Ker}(\alpha)$ , use also that the maps  $\alpha_{p,q,i} : A_i^{p,q} \otimes S^{p,q}V(i) \rightarrow B_i^{p,q} \otimes S^{p,q}V(i)$  are zero). Then 2 holds. The other implication is completely analogous to the implication "if" of *i*.

*ii*) Suppose  $\alpha$  is injective. Fix  $q$  and  $r$ . Let  $\underline{p} = \min\{p \mid A^{p,q,r} \neq 0\}$  and let

$$\psi_{\underline{p}} = \oplus_{p \geq \underline{p}} I_{A^{p,q,r}} \otimes \varphi_{p,\underline{p}} : (\oplus_{p \geq \underline{p}} A^{p,q,r}) \otimes S^{p,q,r}V(p+q+r) \rightarrow \oplus_{p \geq \underline{p}} A^{p,q,r} \otimes S^{p,q,r}V(p+q+r)$$

It holds

$$\alpha_{q,r} \circ \psi_{\underline{p}} = (\oplus_{\rho} I_{B^{\rho,q,r}} \otimes \varphi_{\rho,\underline{p}}) \circ (M(\alpha_{q,r}) \otimes I_{S^{p,q,r}V(p+q+r)})$$

Let  $v \in \text{Ker}M(\alpha_{q,r})$ . If  $v \neq 0$  then  $\psi_{\underline{p}}(v \otimes y_{\underline{p},q,r}^{p+q+r})$  (see Lemma 11 for the definition of  $y_{\underline{p},q,r}^{p+q+r}$ ) is nonzero (since  $\psi_{\underline{p}}$  is injective) and it is in  $\text{Ker}(\alpha)$  (in fact it is in  $\text{Ker}(\alpha_{q,r})$  by the above formula and thus in  $\text{Ker}(\alpha)$  by the definition of  $y_{\underline{p},q,r}^{p+q+r}$ ). Hence we get a contradiction since  $\alpha$  is injective, therefore  $v = 0$ . Thus  $M(\alpha_{q,r})$  is injective; hence  $\alpha_{q,r}$  is injective by Lemma 13.

Now suppose  $\alpha_{q,r}$  is injective  $\forall q, r$ . Observe that  $\alpha$  is "triangular" with respect to  $q$  and  $r$ , thus, if  $\forall q$  the induced map

$$\alpha_q : \oplus_{p,r} A^{p,q,r} \otimes S^{p,q,r}V(p+q+r) \rightarrow \oplus_{p,r} B^{\rho,q,r} \otimes S^{\rho,q,r}V(\rho+q+r)$$

is injective then  $\alpha$  is injective; besides  $\alpha_q$  is injective  $\forall q$  if  $\forall q, r$  the induced map  $\alpha_{q,r}$  is injective.  $\square$

Theorem 9 is easily generalizable to  $\mathbf{P}^n$ . Obviously the statement on minimal resolutions is generalizable to minimal free resolutions with two terms of bundles on  $\mathbf{P}^n$ , but for a generic homogeneous bundle on  $\mathbf{P}^n$  with  $n \geq 3$  the minimal free resolution has more than two terms.

Finally we observe that Theorem 2 and the following lemma (which will be useful also later to study simplicity) allow us to parametrize the set of homogeneous bundles on  $\mathbf{P}^2$  by a set of sequences of injective matrices with a certain shape up to the action of invertible matrices with a certain shape.

**Lemma 14** *i)* Let  $E$  and  $E'$  be two homogeneous vector bundles on  $\mathbf{P}^2$  and

$$a) \quad 0 \rightarrow R \xrightarrow{f} S \xrightarrow{g} E \rightarrow 0 \quad b) \quad 0 \rightarrow R' \xrightarrow{f'} S' \xrightarrow{g'} E' \rightarrow 0 \quad (5)$$

be two minimal free resolutions. Any map  $\eta : E \rightarrow E'$  induces maps  $A$  and  $B$  s.t. the following diagram commutes:

$$\begin{array}{ccccccc} 0 & \rightarrow & R & \xrightarrow{f} & S & \xrightarrow{g} & E & \rightarrow 0 \\ & & \downarrow A & & \downarrow B & & \downarrow \eta & \\ 0 & \rightarrow & R' & \xrightarrow{f'} & S' & \xrightarrow{g'} & E' & \rightarrow 0 \end{array}$$

and given  $A$  and  $B$  s.t. the above diagram commutes we have a map  $E \rightarrow E'$ . Given  $\eta$ , the maps  $A$  and  $B$  are unique if and only if  $\text{Hom}(S, R') = 0$ . (In particular if  $\text{Hom}(S, R') = 0$  and we find  $A$  and  $B$  s.t. the diagram commutes and  $B$  is not a multiple of the identity, we can conclude that  $E$  is not simple.)

ii) Let

$$a) \quad 0 \rightarrow R \xrightarrow{f} S \xrightarrow{g} E \rightarrow 0 \quad b) \quad 0 \rightarrow R \xrightarrow{f'} S \xrightarrow{g'} E \rightarrow 0 \quad (6)$$

be two minimal free resolutions with  $SL(V)$ -invariant maps of a homogeneous bundle  $E$  on  $\mathbf{P}^2 = \mathbf{P}(V)$ ; then there exist  $SL(V)$ -invariant automorphisms  $A : R \rightarrow R$ ,  $B : S \rightarrow S$  s.t. the following diagram commutes:

$$\begin{array}{ccccccc} 0 \rightarrow & R & \xrightarrow{f} & S & \xrightarrow{g} & E & \rightarrow 0 \\ & \downarrow A & & \downarrow B & & \downarrow \text{Id} & \\ 0 \rightarrow & R & \xrightarrow{f'} & S & \xrightarrow{g'} & E & \rightarrow 0 \end{array}$$

*Proof.* i) The composition  $S \xrightarrow{g} E \xrightarrow{\eta} E'$  can be lifted to a map  $B : S \rightarrow S'$  by the exact sequence  $0 \rightarrow \text{Hom}(S, R') \rightarrow \text{Hom}(S, S') \rightarrow \text{Hom}(S, E') \rightarrow 0$  (obtained by applying  $\text{Hom}(S, \cdot)$  to (5)b). By the exact sequence  $\text{Hom}(R, R') \rightarrow \text{Hom}(R, S') \rightarrow \text{Hom}(R, E')$  (obtained by applying  $\text{Hom}(R, \cdot)$  to (5)b) the composition  $R \xrightarrow{f} S \xrightarrow{B} S'$ , which goes to zero in  $\text{Hom}(R, E')$ , can be lifted to a map  $A : R \rightarrow R'$ .

ii) As in i we can prove there exist  $SL(V)$ -invariant maps  $B : S \rightarrow S$  and  $B' : S \rightarrow S$  s.t. the following diagrams commute

$$\begin{array}{ccccc} 0 \rightarrow & R & \xrightarrow{f} & S & \xrightarrow{g} & E & \rightarrow 0 \\ & & \downarrow B & & \downarrow \text{Id} & & \\ 0 \rightarrow & R & \xrightarrow{f'} & S & \xrightarrow{g'} & E & \rightarrow 0 & \end{array} \quad \begin{array}{ccccc} 0 \rightarrow & R & \xrightarrow{f'} & S & \xrightarrow{g'} & E & \rightarrow 0 \\ & & \downarrow B' & & \downarrow \text{Id} & & \\ 0 \rightarrow & R & \xrightarrow{f} & S & \xrightarrow{g} & E & \rightarrow 0 & \end{array}$$

then we get the commutative diagram

$$\begin{array}{ccccccc} 0 \rightarrow & R & \xrightarrow{f} & S & \xrightarrow{g} & E & \rightarrow 0 \\ & & & \downarrow B' \circ B & & \downarrow \text{Id} & \\ 0 \rightarrow & R & \xrightarrow{f} & S & \xrightarrow{g} & E & \rightarrow 0 \end{array}$$

Since also  $\text{Id} : S \rightarrow S$  lifts  $\text{Id} : E \rightarrow E$  in the above diagram (i.e.  $\text{Id} \circ g = g \circ \text{Id}$ ), there exists a map  $a : S \rightarrow R$  s.t.  $B' \circ B - \text{Id} = f \circ a$ ; hence, by the minimality of (6)a,  $\det(B' \circ B) = 1 + P$  where  $P$  is a polynomial without terms of degree 0; since  $\det(B' \circ B) : \det(S) \rightarrow \det(S)$  must be homogeneous,  $P = 0$ ; hence  $B' \circ B$  is invertible and thus  $B$  is invertible.  $\square$

## 4 Quivers

We recall now the main definitions and results on quivers and representations of quivers associated to homogeneous bundles introduced by Bondal and Kapranov in [B-K]. The quivers will allow us to handle well and “to make explicit” the homogeneous subbundles of a homogeneous bundle.

**Definition 15** (See [Sim], [King], [Hil1], [G-R].) A **quiver** is an oriented graph  $\mathcal{Q}$  with the set  $\mathcal{Q}_0$  of vertices (or points) and the set  $\mathcal{Q}_1$  of arrows.

A **path** in  $\mathcal{Q}$  is a formal composition of arrows  $\beta_m \dots \beta_1$  where the source of an arrow  $\beta_i$  is the sink of the previous arrow  $\beta_{i-1}$ .

A **relation** in  $\mathcal{Q}$  is a linear form  $\lambda_1 c_1 + \dots + \lambda_r c_r$  where  $c_i$  are paths in  $\mathcal{Q}$  with a common source and a common sink and  $\lambda_i \in \mathbf{C}$ .

A **representation of a quiver**  $\mathcal{Q} = (\mathcal{Q}_0, \mathcal{Q}_1)$ , or  $\mathcal{Q}$ -**representation**, is the couple of a set of vector spaces  $\{X_i\}_{i \in \mathcal{Q}_0}$  and of a set of linear maps  $\{\varphi_\beta\}_{\beta \in \mathcal{Q}_1}$  where  $\varphi_\beta : X_i \rightarrow X_j$  if  $\beta$  is an arrow from  $i$  to  $j$ .

A **representation of a quiver  $\mathcal{Q}$  with relations  $\mathcal{R}$**  is a  $\mathcal{Q}$ -representation s.t.

$$\sum_j \lambda_j \varphi_{\beta_{m_j}^j} \dots \varphi_{\beta_1^j} = 0$$

for every  $\sum_j \lambda_j \beta_{m_j}^j \dots \beta_1^j \in \mathcal{R}$ .

Let  $(X_i, \varphi_\beta)_{i \in \mathcal{Q}_0, \beta \in \mathcal{Q}_1}$  and  $(Y_i, \psi_\beta)_{i \in \mathcal{Q}_0, \beta \in \mathcal{Q}_1}$  be two representations of a quiver  $\mathcal{Q} = (\mathcal{Q}_0, \mathcal{Q}_1)$ . A **morphism**  $f$  from  $(X_i, \varphi_\beta)_{i \in \mathcal{Q}_0, \beta \in \mathcal{Q}_1}$  to  $(Y_i, \psi_\beta)_{i \in \mathcal{Q}_0, \beta \in \mathcal{Q}_1}$  is a set of linear maps  $f_i : X_i \rightarrow Y_i$ ,  $i \in \mathcal{Q}_0$  s.t., for every  $\beta \in \mathcal{Q}_1$ ,  $\beta$  arrow from  $i$  to  $j$ , the following diagram is commutative:

$$\begin{array}{ccc} X_i & \xrightarrow{f_i} & Y_i \\ \varphi_\beta \downarrow & & \downarrow \psi_\beta \\ X_j & \xrightarrow{f_j} & Y_j \end{array}$$

A morphism  $f$  is injective if the  $f_i$  are injective.

**Notation 16** We will say that a representation  $(X_i, \varphi_\beta)_{i \in \mathcal{Q}_0, \beta \in \mathcal{Q}_1}$  of a quiver  $\mathcal{Q} = (\mathcal{Q}_0, \mathcal{Q}_1)$  has **multiplicity**  $m$  in a point  $i$  of  $\mathcal{Q}$  if  $\dim X_i = m$ .

The **support** (with multiplicities) of a representation of a quiver  $\mathcal{Q}$  is the subgraph of  $\mathcal{Q}$  constituted by the points of multiplicity  $\geq 1$  and the nonzero arrows (with the multiplicities associated to every point of the subgraph).

We recall now from [B-K], [Hil1], [Hil2] the definition of a quiver  $\mathcal{Q}$  s.t. the category of the homogeneous bundles on  $\mathbf{P}^2$  is equivalent to the category of finite dimensional representations of  $\mathcal{Q}$  with some relations  $\mathcal{R}$ . Bondal and Kapranov defined such a quiver in a more general setting but we recall such a construction only for  $\mathbf{P}^2$ . See also [O-R].

First some notation. Let  $P$  and  $R$  be the following subgroup of  $SL(3)$ :

$$P = \left\{ \begin{pmatrix} a & b & c \\ 0 & d & e \\ 0 & f & g \end{pmatrix} \in SL(3) \right\} \quad R = \left\{ \begin{pmatrix} a & 0 & 0 \\ 0 & d & e \\ 0 & f & g \end{pmatrix} \in SL(3) \right\}$$

Observe that  $R$  is reductive. We can see  $\mathbf{P}^2$  as

$$\mathbf{P}^2 = SL(3)/P$$

( $P$  is the stabilizer of  $[1 : 0 : 0]$ ). Let  $p$  and  $r$  be the Lie algebras associated respectively to  $P$  and  $R$ . Let  $n$  be the Lie algebra

$$n = \left\{ \begin{pmatrix} 0 & x & y \\ 0 & 0 & 0 \\ 0 & 0 & 0 \end{pmatrix} \mid x, y \in \mathbf{C} \right\}$$

Thus  $p = r \oplus n$  (Levi decomposition).

We recall that the homogeneous bundles on  $\mathbf{P}^2 = SL(3)/P$  are given by the representations of  $P$  (this bijection is given by taking the fibre over  $[1 : 0 : 0]$  of a homogeneous vector bundle); by composing the projection from  $P$  to  $R$  with a representation of  $R$  we get a representation of  $P$  and the set of the homogenous bundles obtained in this way from the irreducible representations of  $R$  are

$$\{S^l Q(t) \mid l \in \mathbf{N}, t \in \mathbf{Z}\}$$

where  $Q = T_{\mathbf{P}^2}(-1)$ ;

**Definition 17** *From now on  $\mathcal{Q}$  will be the following quiver:*

- *let*

$$\begin{aligned} \mathcal{Q}_0 &= \{\text{irreducible representations of } R\} = \{S^l Q(t) \mid l \in \mathbf{N}, t \in \mathbf{Z}\} = \\ &= \{\text{dominant weights of } r\} \end{aligned}$$

- *let  $\mathcal{Q}_1$  be defined in the following way: there is an arrow from  $\lambda$  to  $\mu$ ,  $\lambda, \mu \in \mathcal{Q}_0$ , if and only if  $n \otimes \Sigma_\lambda \supset \Sigma_\mu$ , where  $\Sigma_\lambda$  denotes the representation of  $r$  with dominant weight  $\lambda$ .*

**Lemma 18** *The adjoint representation of  $p$  on  $n$  corresponds to  $Q(-2) = \Omega^1$ , more precisely: let  $\rho: p \rightarrow gl(n)$  be the following representation:*

$$\rho(B)h\begin{pmatrix} x \\ y \end{pmatrix} = Bh\begin{pmatrix} x \\ y \end{pmatrix} - h\begin{pmatrix} x \\ y \end{pmatrix}B$$

where  $h: \mathbf{C}^2 \rightarrow n$  is the isomorphism  $\begin{pmatrix} x \\ y \end{pmatrix} \mapsto \begin{pmatrix} 0 & x & y \\ 0 & 0 & 0 \\ 0 & 0 & 0 \end{pmatrix}$ ;  $Q(-2)$  is the homogeneous bundle whose fibre as  $p$ -representation is  $n$ .

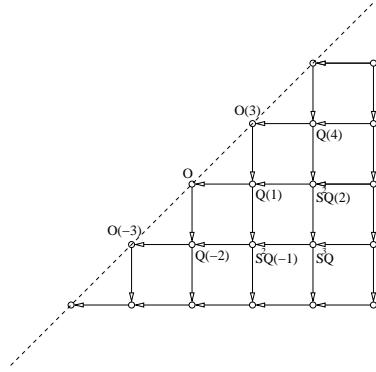
*Proof.* Observe that if  $B = \begin{pmatrix} a & b & c \\ 0 & d & e \\ 0 & f & g \end{pmatrix} \in p$  and  $A = \begin{pmatrix} d & e \\ f & g \end{pmatrix}$  then

$$h^{-1}(Bh\begin{pmatrix} x \\ y \end{pmatrix} - h\begin{pmatrix} x \\ y \end{pmatrix}B) = (a \text{Id} - {}^t A)\begin{pmatrix} x \\ y \end{pmatrix};$$

since the representation  $p \rightarrow gl(1)$ ,  $B \mapsto a \text{Id}$  corresponds to the bundle  $\mathcal{O}(-1)$  and the representation  $p \rightarrow gl(2)$ ,  $B \mapsto -^t A$  corresponds to the bundle  $Q^\vee = Q(-1)$ , we conclude.  $\square$

By the previous remark, if  $\Sigma_\lambda$  is the representation corresponding to  $S^l Q(t)$  and  $\Sigma_\mu$  is the representation corresponding to  $S^{l'} Q(t')$ , the condition  $n \otimes \Sigma_\lambda \supset \Sigma_\mu$  is equivalent to the fact  $S^{l'} Q(t')$  is a direct summand of  $Q(-2) \otimes S^l Q(t)$  and this is true if and only if  $(l', t') = (l-1, t-1)$  or  $(l', t') = (l+1, t-2)$  (we recall that, by the Euler sequence,  $\wedge^2 Q = \mathcal{O}(1)$ ).

Thus our quiver has three connected components  $\mathcal{Q}^{(1)}$ ,  $\mathcal{Q}^{(2)}$ ,  $\mathcal{Q}^{(3)}$  (given by the congruence class modulo  $3/2$  of the slope of the homogeneous vector bundles corresponding to the points of the connected component); the figure shows one of them (the one whose points correspond to the bundles with  $\mu \equiv 0 \pmod{3/2}$ ): we identify the points of every connected component  $\mathcal{Q}^{(j)}$  of  $\mathcal{Q}$  with a subset of  $\mathbf{Z}^2$  for convenience.



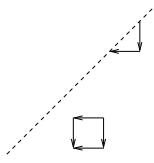
**Definition 19** Let  $\mathcal{R}$  be the set of relations on  $\mathcal{Q}$  given by the commutativity of the squares, i.e. (denoting by  $\beta_{w,v}$  the arrow from  $v$  to  $w$ ):

$$\beta_{(x-1,y-1),(x-1,y)} \beta_{(x-1,y),(x,y)} - \beta_{(x-1,y-1),(x,y-1)} \beta_{(x,y-1),(x,y)}$$

$\forall (x,y) \in \mathcal{Q}^{(j)} \subset \mathbf{Z}^2$  for some  $j$ , s.t.  $(x-1,y) \in \mathcal{Q}$  and

$$\beta_{(x-1,y-1),(x,y-1)} \beta_{(x,y-1),(x,y)}$$

$\forall (x,y) \in \mathcal{Q}^{(j)} \subset \mathbf{Z}^2$  for some  $j$ , s.t.  $(x-1,y) \notin \mathcal{Q}$ .



**Definition 20** Let  $E$  be a homogeneous vector bundle on  $\mathbf{P}^2$ . The  $\mathcal{Q}$ -representation associated to  $E$  is the following (see [B-K], [Hil1], [Hil2], [O-R]): consider the fiber  $E_{[1:0:0]}$  of  $E$  on  $[1 : 0 : 0]$ ; it is a representation of  $p$ ; as  $r$ -representation we have

$$E_{[1:0:0]} = \bigoplus_{\lambda \in \mathcal{Q}_0} X_\lambda \otimes \Sigma_\lambda$$

for some vector spaces  $X_\lambda$ ; we associate to  $\lambda \in \mathcal{Q}_0$  the vector space  $X_\lambda$ ; we fix  $\forall \lambda$  a dominant weight vector  $v_\lambda \in \Sigma_\lambda$  and  $\eta_1, \eta_2$  eigenvectors of the  $p$ -representation  $n$ ; let  $\psi_1, \psi_2$  be their weights respectively; let  $i$  be s.t.  $\lambda + \psi_i = \mu$ ; we associate to an arrow  $\lambda \rightarrow \mu$  a map  $f : X_\lambda \rightarrow X_\mu$  defined in the following way: consider the composition

$$\Sigma_\lambda \otimes n \otimes X_\lambda \longrightarrow \Sigma_\mu \otimes X_\mu$$

given by the action of  $n$  over  $E_{[1:0:0]}$  followed by projection; it maps  $v_\lambda \otimes \eta_i \otimes v$  to  $v_\mu \otimes w$ ; we define  $f(v) = w$  (it does not depend on the choice of the dominant weight vector).

**Theorem 21 (Bondal, Kapranov, Hille)** [B-K], [Hil1], [Hil2], [O-R]. The category of the homogeneous bundles on  $\mathbf{P}^2$  is equivalent to the category of finite dimensional representation of the quiver  $\mathcal{Q}$  with the relations  $\mathcal{R}$ .

Observe that in Def. 20 with respect to Bondal-Kapranov-Hille's convention in [B-K], [Hil1], [Hil2], we preferred to invert the arrows in order that an injective  $SL(V)$ -equivariant map of bundles corresponds to an injective morphism of  $\mathcal{Q}$ -representations. For example  $\mathcal{O}$  injects in  $V(1)$  whose support is the arrow from  $Q(1)$  to  $\mathcal{O}$ .

$$\begin{array}{ccc} & \circlearrowleft & \circlearrowright \\ \mathcal{O} & & Q(1) \end{array}$$

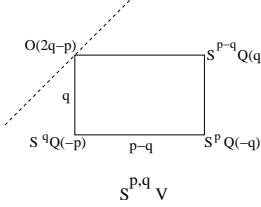
**Notation 22** • We will often speak of the  $\mathcal{Q}$ -support of a homogeneous bundle  $E$  instead of the support with multiplicities of the  $\mathcal{Q}$ -representation of  $E$  and we will denote it by  $\mathcal{Q}\text{-supp}(E)$ .

• The word “rectangle” will denote the subgraph with multiplicities of  $\mathcal{Q}$  given by the subgraph of  $\mathcal{Q}$  included in a rectangle whose sides are unions of arrows of  $\mathcal{Q}$ , with the multiplicities of all its points equal to 1.

The word “segment” will denote a rectangle with base or height equal to 0.

• If  $A$  and  $B$  are two subgraphs of  $\mathcal{Q}$ ,  $A \cap B$  is the subgraph of  $\mathcal{Q}$  whose vertices and arrows are the vertices and arrows both of  $A$  and of  $B$ ;  $A - B$  is the subgraph of  $\mathcal{Q}$  whose vertices are the vertices of  $A$  not in  $B$  and the arrows are the arrows of  $A$  joining two vertices of  $A - B$ .

**Remark 23** ([B-K]) The  $\mathcal{Q}$ -support of  $S^{p,q}V$  is a rectangle as in the figure:



In fact: by the Euler sequence  $S^{p,q}V = S^{p,q}(\mathcal{O}(-1) \oplus Q)$  as  $R$ -representation; by the formula of a Schur functor applied to a direct sum (see [F-H], Exercise 6.11) we get

$$S^{p,q}V = \bigoplus S^\lambda Q \otimes S^m \mathcal{O}(-1)$$

as  $R$ -representations, where the sum is performed on  $m \in \mathbf{N}$  and on  $\lambda$  Young diagram obtained from the Young diagram of  $(p, q)$  by taking off  $m$  boxes not two in the same column; thus

$$S^{p,q}V = \bigoplus_{0 \leq m_1 \leq p-q, 0 \leq m_2 \leq q} S^{p-m_1, q-m_2} Q(-m_1 - m_2)$$

Finally to show the maps associated to the arrows in the rectangle are nonzero we can consider on the set of the vertices of the rectangle the following equivalence relation:  $P \sim Q$  if and only if there exist two paths with  $P$  and  $Q$  respectively as sources and common sink s.t. the map associated to any arrow of the two paths is nonzero; if a map associated to an arrow (say from  $P_1$  to  $P_2$ ) of the rectangle is zero then, by the ‘‘commutativity of the squares’’, precisely by the relations in Definition 19, there would be at least two equivalence classes (the class of  $P_1$  and the class of  $P_2$ ), but this is impossible by the irreducibility of  $S^{p,q}V$ .

## 5 Some lemmas and notation

In this section we study equivariant maps between some homogeneous bundles on  $\mathbf{P}^2$  by using the language of the quivers and we collect some technical notation and lemmas, which will be useful in the next section to study homogeneous subbundles (in particular their slope) of homogeneous bundles and then to study stability.

### 5.1 $\mathcal{Q}$ -representation of kernels and images

**Lemma 24** *Let  $\varphi : S^{p,q}V \rightarrow S^{p+s_1, q+s_2, s_3}V(s_1 + s_2 + s_3)$  be an  $SL(V)$ -invariant nonzero map; then*

- i)  $\mathcal{Q}\text{-supp}(Ker(\varphi)) = \mathcal{Q}\text{-supp}(S^{p,q}V) - \mathcal{Q}\text{-supp}(S^{p+s_1, q+s_2, s_3}V(s_1 + s_2 + s_3))$
- ii)  $\mathcal{Q}\text{-supp}(Im(\varphi)) = \mathcal{Q}\text{-supp}(S^{p,q}V) \cap \mathcal{Q}\text{-supp}(S^{p+s_1, q+s_2, s_3}V(s_1 + s_2 + s_3))$
- iii)  $\mathcal{Q}\text{-supp}(Coker(\varphi)) = \mathcal{Q}\text{-supp}(S^{p+s_1, q+s_2, s_3}V(s_1 + s_2 + s_3)) - \mathcal{Q}\text{-supp}(S^{p,q}V).$

*Proof.* Consider the  $P$ -invariant (and thus  $R$ -invariant) map  $\varphi_{[1:0:0]}$  induced by  $\varphi$  on the fibers on  $[1 : 0 : 0]$ ; it is the morphism from the  $\mathcal{Q}$ -representation of  $S^{p,q}V$  to the  $\mathcal{Q}$ -representation of  $S^{p+s_1, q+s_2, s_3}V(s_1 + s_2 + s_3)$ .

Obviously the  $R$ -representations corresponding to the vertices in the  $\mathcal{Q}$ -support of  $S^{p,q}V$  and not in the  $\mathcal{Q}$ -support of  $S^{p+s_1,q+s_2,s_3}V(s_1 + s_2 + s_3)$  are in  $\text{Ker}\varphi_{[1:0:0]}$ . We have to show that the  $R$ -representations corresponding to the vertices both in the  $\mathcal{Q}$ -support of  $S^{p,q}V$  and in the  $\mathcal{Q}$ -support of  $S^{p+s_1,q+s_2,s_3}V(s_1 + s_2 + s_3)$  are not in  $\text{Ker}\varphi_{[1:0:0]}$ . We call  $I$  the set of such vertices. If the  $R$ -representation corresponding to an element of  $I$  is in  $\text{Ker}\varphi_{[1:0:0]}$ , then also the  $R$ -representation corresponding to another element of  $I$  is in  $\text{Ker}\varphi_{[1:0:0]}$ : in fact by the commutativity of the diagram in the definition of morphism of representations of a quiver, if the  $R$ -representation corresponding to  $\lambda \in I$  is in  $\text{Ker}\varphi_{[1:0:0]}$ , then also the  $R$ -representation corresponding to any element of  $I$  linked to  $\lambda$  by an arrow is in  $\text{Ker}\varphi_{[1:0:0]}$  and we conclude since  $\forall \lambda_1, \lambda_2 \in I$  there is a path of the quiver joining  $\lambda_1$  and  $\lambda_2$ . Thus either any  $R$ -representation corresponding to an element of  $I$  is in  $\text{Ker}\varphi_{[1:0:0]}$  or any  $R$ -representation corresponding to an element of  $I$  is not in  $\text{Ker}\varphi_{[1:0:0]}$ . But the last case is impossible because  $\varphi$  is nonzero.  $\square$

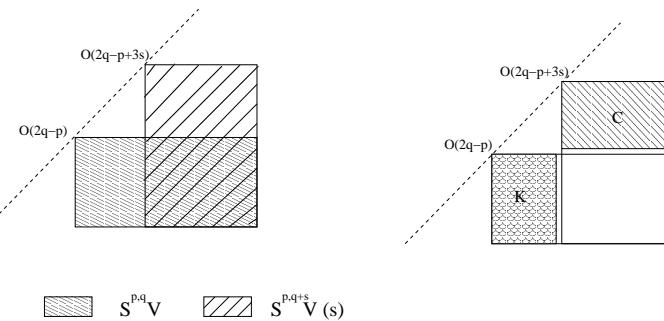
**Corollary 25** *Let  $\varphi : S^{p,q}V \rightarrow \bigoplus_{s_1,s_2,s_3} S^{p+s_1,q+s_2,s_3}V(s_1 + s_2 + s_3)$  (where the sum is on a finite subset of  $\mathbb{N}^3$ ) be an  $SL(V)$ -invariant nonzero map. Then  $\mathcal{Q}\text{-supp}(\text{Ker}(\varphi)) = \mathcal{Q}\text{-supp}(S^{p,q}V) - \mathcal{Q}\text{-supp}(\bigoplus S^{p+s_1,q+s_2,s_3}V(s_1 + s_2 + s_3))$ .*

**Lemma 26 (Four Terms Lemma.)** *On  $\mathbf{P}^2 = \mathbf{P}(V)$  we have the following exact sequence:*

$$0 \rightarrow S^{q+s-1,q}V(-p+q-1+s) \rightarrow S^{p,q}V \rightarrow S^{p,q+s}V(s) \rightarrow S^{p-q-1,s-1}V(q+1+s) \rightarrow 0$$

where the maps are  $SL(V)$ -invariant nonzero maps (they are unique up to multiples). (Observe that  $S^{p-q-1,s-1}V(q+1+s) \simeq S^{p,q+s,q+1}V(q+1+s)$ .)

*Proof.* In the figure we show the sides of the  $\mathcal{Q}$ -supports of  $S^{p,q}V$  and  $S^{p,q+s}V(s)$ :



these supports are rectangles (see Remark 23); thus by Lemma 24 the  $\mathcal{Q}$ -support of the kernel of  $S^{p,q}V \rightarrow S^{p,q+s}V(s)$  is the rectangle  $K$ , which is the  $\mathcal{Q}$ -support of  $S^{q+s-1,q}V(-p+q-1+s)$  and the  $\mathcal{Q}$ -support of the cokernel of  $S^{p,q}V \rightarrow S^{p,q+s}V(s)$  is the rectangle  $C$ , which is the support of  $S^{p-q-1,s-1}V(q+1+s)$ .  $\square$

## 5.2 Some calculations on the slope

**Remark 27** i) The first Chern class of a homogeneous bundle  $E$  can be calculated as the sum of the first Chern classes of the irreducible bundles corresponding to the vertices of the  $\mathcal{Q}$ -support of  $E$  multiplied by the multiplicities. The rank of  $E$  is the sum of the ranks of the irreducible bundles corresponding to such vertices multiplied by the multiplicities.

We will often speak of the slope (resp. first Chern class, rank) of a graph with multiplicities instead of the slope (resp. first Chern class, rank) of the vector bundle whose  $\mathcal{Q}$ -support is that graph with multiplicities.

ii) Suppose the set of the vertices of the  $\mathcal{Q}$ -support of  $E$  is the disjoint union of the vertices of the supports of two  $\mathcal{Q}$ -representations  $A$  and  $B$ ; if  $\mu(A) = \mu(B)$  then  $\mu(E) = \mu(A) = \mu(B)$ , if  $\mu(A) < \mu(B)$  then  $\mu(A) < \mu(E) < \mu(B)$ .

iii) We recall that the rank of  $S^l Q(t)$  is  $l+1$  and its first Chern class is  $(l+1)(l/2+t)$ .

**Lemma 28** *Let  $R$  be a rectangle of base  $h$ , height  $k$  and  $S^l Q(t)$  as the highest vertex of the left side. Then*

$$\mu(R) = \frac{(h+1)(k+1)[\frac{h^2-k^2}{2} + h(l+\frac{t}{2}+1) + k(\frac{t}{2}-\frac{l}{2}-1) + (l+1)(\frac{l}{2}+t)]}{(h+1)(k+1)(l+\frac{h+k}{2}+1)}$$

(where the numerator is the first Chern class and the denominator is the rank.)

*Proof.* Left to the reader. □

**Lemma 29** *Let  $S$  be a horizontal (resp. vertical) segment in  $\mathcal{Q}^{(j)}$  for some  $j$  and let  $S'$  be obtained translating  $S$  by  $(0, 1)$  (resp  $(1, 0)$ ) in  $\mathcal{Q}^{(j)} \subset \mathbf{Z}^2$ . Then  $\mu(S) < \mu(S')$ .*

$$\begin{array}{c} \overline{s'} \\ \overline{s} \end{array} \quad \begin{array}{c} | \\ s \end{array} \quad \begin{array}{c} | \\ s' \end{array}$$

*Proof.* Suppose  $S$  is horizontal, of length  $h$  and its first vertex from left is  $S^l Q(t)$ . By Lemma 28,

$$\mu(S') = \frac{h^2 + 2h(l+1) + l(l+1)}{2l+2+h} + t$$

$$\mu(S) = \frac{h^2 + 2h(l+2) + (l+2)(l+1)}{2(l+1)+2+h} + t - 2$$

and  $\mu(S') > \mu(S)$  is easy to check. The case of vertical segments is similar. □

**Lemma 30** i) *Let  $U$  and  $U'$  be two rectangles with the same base with the vertical sides lined up and  $U$  above  $U'$ . Then  $\mu(U') < \mu(U)$ .*

ii) *Let  $W$  and  $W'$  be two rectangles with the same height and the horizontal sides lined up and  $W$  at the right side of  $W'$ . Then  $\mu(W') < \mu(W)$ .*

iii) Let  $R$  be a rectangle and  $R'$  a subrectangle of  $R$  with the same base and with the lower side equal to the lower side of  $R$ . Then  $\mu(R') < \mu(R)$ .

iv) Let  $T$  be a rectangle and  $T'$  a subrectangle of  $T$  with the same height and with the left side equal to the left side of  $T$ . Then  $\mu(T') < \mu(T)$ .



*Proof.* i) By Lemma 29 and Remark 27 the slope of a rectangle is between the slope of the lower side and the slope of the higher side, thus again by Lemma 29 we conclude.

ii) Analogous to i.

iii) and iv) follow from i and ii.  $\square$

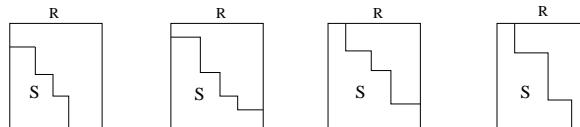
### 5.3 Staircases

In this subsection we introduce particular  $\mathcal{Q}$ -representations, called “staircases”. Their importance is due to the fact that they are the  $\mathcal{Q}$ -supports of the homogeneous subbundles of the homogeneous bundles whose  $\mathcal{Q}$ -supports are rectangles (in particular of the trivial homogeneous bundles).

**Remark 31** Let  $E$  be a homogeneous bundle on  $\mathbf{P}^2$  and  $F$  be a homogeneous subbundle. Let  $S$  and  $S'$  be the  $\mathcal{Q}$ -supports of  $E$  and  $F$  respectively. By Theorem 21 the  $\mathcal{Q}$ -representation of  $F$  injects into the  $\mathcal{Q}$ -representation of  $E$ . If the multiplicities of  $S$  are all 1 and  $S'$  contains the source of an arrow  $\beta$  in  $S$  then  $S'$  contains  $\beta$ .

**Definition 32** We say that a subgraph with multiplicities of  $\mathcal{Q}$  is a **staircase**  $S$  in a rectangle  $R$  if all its multiplicities are 1 and the graph of  $S$  is a subgraph of  $R$  satisfying the following property: if  $V$  is a vertex of  $S$  then the arrows of  $R$  having  $V$  as source must be arrows of  $S$  (and then also their sinks must be vertices of  $S$ ). We say that a subgraph with multiplicities of  $\mathcal{Q}$  is a **staircase** if it is a staircase in some rectangle.

Observe that a staircase  $S$  in a rectangle  $R$  has as matter of fact the form of a staircase with base and left side included respectively in the base and the left side of  $R$  as in the figure below. By Remark 31 the  $\mathcal{Q}$ -support of a homogeneous subbundle of a homogeneous bundle whose  $\mathcal{Q}$ -support is a rectangle is a staircase in the rectangle.



**Notation 33** (See the figure below). Given a staircase  $S$  in a rectangle we define  $\mathcal{V}_S$  to be the set of the vertices of  $S$  that are not sinks of any arrow of  $S$ . We call the elements of  $\mathcal{V}_S$  the **vertices of the steps**. Let  $\mathcal{V}_S = \{V_1, \dots, V_k\}$  ordered in such a way the projection of  $V_{i+1}$  on the base of  $R$  is on the left of the projection of  $V_i$   $\forall i = 1, \dots, k-1$ .

We define  $R_i$  as the rectangles with the right higher vertex equal to  $V_i$  and left lower vertex equal to the left lower vertex of  $R$ .

For any  $i = 1, \dots, k$ , we define the  **$i$ -th horizontal step**

$$H_i = R_i - R_{i-1}$$

$(R_0 = \emptyset)$  and the  **$i$ -th vertical step**

$$E_i = R_i - R_{i+1}$$

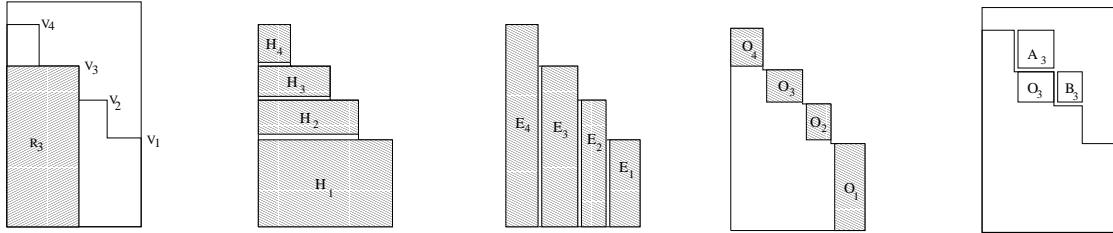
$(R_{k+1} = \emptyset)$ . We define the  **$i$ -th sticking out part** as  $O_i = H_i \cap E_i$ .

Let  $s_i$  and  $r_i$  be the lines containing respectively the higher side of  $O_i$  and the right side of  $O_i$ .

For  $i = 1, \dots, k-1$ , let  $S_i$  be the rectangle whose sides are on  $r_i, s_{i+1}$ , the line of the base of the staircase and the line on the left side of the staircase.

Let  $A_i$   $i = 1, \dots, k-1$  and  $B_i$   $i = 2, \dots, k$  be the rectangles

$$A_i = S_i - R_i - R_{i+1} \quad B_i = S_{i-1} - R_i - R_{i-1}$$



## 6 Results on stability and simplicity of elementary homogeneous bundles

**Definition 34** We say that a  $G$ -homogeneous bundle is multistable if it is the tensor product of a stable  $G$ -homogeneous bundle and an irreducible  $G$ -representation.

**Theorem 35 (Rohmfeld, Faini)** *i) [Rohm] A homogeneous bundle  $E$  is semistable if and only if  $\mu(F) \leq \mu(E)$  for any subbundle  $F$  of  $E$  induced by a subrepresentation of the  $P$ -representation inducing  $E$ .*

*ii) [Fa] A homogeneous bundle  $E$  is multistable if and only if  $\mu(F) < \mu(E)$  for any subbundle  $F$  of  $E$  induced by a subrepresentation of the  $P$ -representation inducing  $E$ .*

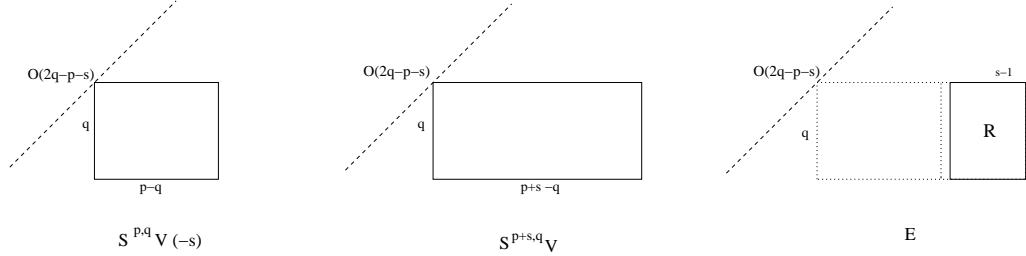
**Theorem 36** Let  $p, q \in \mathbf{N}$  with  $p \geq q$  and  $s > 0$ . Let  $E$  be the homogeneous vector bundle on  $\mathbf{P}^2 = \mathbf{P}(V)$  defined by the following exact sequence:

$$0 \rightarrow S^{p,q}V(-s) \xrightarrow{\varphi} S^{p+s,q}V \rightarrow E \rightarrow 0 \quad (7)$$

where  $\varphi$  is a nonzero  $SL(V)$ -invariant map. Then  $E$  is stable (in particular it is simple).

*Proof.* To show that  $E$  is stable it is sufficient to show that it is multistable; in fact if  $E$  is the tensor product of a stable homogeneous vector bundle  $E'$  with an  $SL(V)$ -representation  $W$ , then the minimal resolution of  $E$  must be the tensor product of the minimal resolution of  $E'$  with  $W$  and from (7) we must have  $W = \mathbf{C}$ .

To show that  $E$  is multistable we consider the  $\mathcal{Q}$ -representation associated to  $E$ . In the figure we show the sides of the  $\mathcal{Q}$ -supports of  $S^{p,q}V(-s)$  and  $S^{p+s,q}V$ ; these supports are rectangles (see Remark 23); thus the  $\mathcal{Q}$ -support of  $E$  is the rectangle  $R$ :



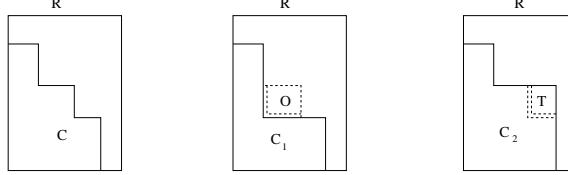
By Theorem 35,  $E$  is multistable if  $\mu(F) < \mu(E)$  for any subbundle  $F$  of  $E$  induced by a subrepresentation of the  $P$ -representation inducing  $E$ . Observe that, by Remark 31, the support of the  $\mathcal{Q}$ -representation of any such subbundle  $F$  must be a staircase  $C$  in  $R$  and vice versa any  $\mathcal{Q}$ -representation whose support is a staircase  $C$  in  $R$  is the  $\mathcal{Q}$ -representation of a subbundle  $F$  of  $E$  induced by a subrepresentation of the  $P$ -representation inducing  $E$ .

We will show by induction on the number  $k$  of steps of  $C$  that  $\mu(C) < \mu(R)$  for any  $C$  staircase in  $R$ .

$k = 1$  In this case  $C$  is a subrectangle in the rectangle  $R$ . Thus this case follows from Lemma 30.

$k - 1 \Rightarrow k$  We will show that, given a staircase  $C$  in  $R$  with  $k$  steps, there exists a staircase  $C'$  in  $R$  with  $k - 1$  steps s.t.  $\mu(C) \leq \mu(C')$ . If we prove this, we conclude because  $\mu(C) \leq \mu(C') < \mu(R)$ , where the last inequality holds by induction hypothesis.

Let  $C_1$  and  $C_2$  be two staircases as in the figure:



that is  $C_1$  and  $C_2$  are staircases with  $k - 1$  steps obtained from  $C$  respectively “removing and adding” two rectangles  $O$  and  $T$ . Precisely  $O$  is a sticking out part  $O_i$  of  $C$  for some  $i$  and  $T$  is a nonempty rectangle among the two rectangles  $A_i, B_i$  (see Notation 33).

If  $\mu(C_1) \geq \mu(C)$  we conclude at once.

Thus we can suppose that  $\mu(C_1) < \mu(C)$ . We state that in this case  $\mu(C_2) \geq \mu(C)$ . In fact: let  $\mu(C_1) = \frac{a}{b}$ ,  $\mu(O) = \frac{c}{d}$  and  $\mu(T) = \frac{e}{f}$ , where the numerators are the first Chern classes and the denominators the ranks; since  $\mu(C_1) < \mu(C)$ , we have  $\frac{a}{b} < \frac{a+c}{b+d}$ , thus  $\frac{a}{b} < \frac{c}{d}$ ; besides by Lemma 30  $\mu(O) < \mu(T)$ , i.e.  $\frac{c}{d} < \frac{e}{f}$ ; thus  $\frac{a+c+e}{b+d+f} \geq \frac{a+c}{b+d}$  i.e.  $\mu(C_2) \geq \mu(C)$ .  $\square$

Observe that, by Lemma 14 *i*, the simplicity statement of Theorem 36 is equivalent to:

**Corollary 37** *Let  $p, q, s \in \mathbf{N}$  with  $p \geq q, s > 0$  and let  $A$  and  $B$  be two linear maps s.t. the following diagram commutes:*

$$\begin{array}{ccc} S^{p,q}V \otimes S^sV & \xrightarrow{\pi} & S^{p+s,q}V \\ A \otimes I \downarrow & & \downarrow B \\ S^{p,q}V \otimes S^sV & \xrightarrow{\pi} & S^{p+s,q}V \end{array}$$

where  $\pi$  is a nonzero  $SL(V)$ -invariant projection (it is unique up to multiple); then  $A = \lambda I$  and  $B = \lambda I$  for some  $\lambda \in \mathbf{C}$ .

Now we want to prove Theorem 3; first it is necessary to prove several lemmas.

**Lemma 38** *Let  $p, q, s \in \mathbf{N}$  with  $p \geq q$ .*

*For every  $M \subset \{(s_1, s_2, s_3) \in \mathbf{N}^3 \mid s_1 + s_2 + s_3 = s, s_2 \leq p - q, s_3 \leq q\}$ , let  $\mathcal{P}_M$  be the following statement: for every  $V$  complex vector space of dimension 3, the commutativity of the diagram of bundles on  $\mathbf{P}(V)$ :*

$$\begin{array}{ccc} S^{p,q}V(-s) & \xrightarrow{\varphi} & \bigoplus_{(s_1, s_2, s_3) \in M} S^{p+s_1, q+s_2, s_3}V \\ A \downarrow & & \downarrow B \\ S^{p,q}V(-s) & \xrightarrow{\varphi} & \bigoplus_{(s_1, s_2, s_3) \in M} S^{p+s_1, q+s_2, s_3}V \end{array}$$

(where  $A$  and  $B$  are linear maps and the components of  $\varphi$  are nonzero  $SL(V)$ -invariant maps) implies  $A = \lambda I$  and  $B = \lambda I$  for some  $\lambda \in \mathbf{C}$ .

Let

$$\{(s_1, s_2, s_3) \in \mathbf{N}^3 \mid s_1 + s_2 + s_3 = s, s_2 \leq p - q, s_3 \leq q\} = R \cup T$$

with  $R \cap T = \emptyset$ ,  $R \neq \emptyset$ ,  $T \neq \emptyset$ .

Then  $\mathcal{P}_R$  is true if and only if  $\mathcal{P}_T$  is true.

*Proof.* Suppose  $\mathcal{P}_T$  is true. We want to show  $\mathcal{P}_R$  is true.

Let  $A$  and  $B$  s.t. the diagram

$$\begin{array}{ccc} S^{p,q}V(-s) & \longrightarrow & \bigoplus_{(s_1,s_2,s_3) \in R} S^{p+s_1,q+s_2,s_3}V \\ A \downarrow & & \downarrow B \\ S^{p,q}V(-s) & \longrightarrow & \bigoplus_{(s_1,s_2,s_3) \in R} S^{p+s_1,q+s_2,s_3}V \end{array}$$

commutes. It is equivalent to the diagram

$$\begin{array}{ccc} S^{p,q}V \otimes S^sV & \xrightarrow{\pi} & \bigoplus_{(s_1,s_2,s_3) \in R} S^{p+s_1,q+s_2,s_3}V \\ A \otimes I \downarrow & & \downarrow B \\ S^{p,q}V \otimes S^sV & \xrightarrow{\pi} & \bigoplus_{(s_1,s_2,s_3) \in R} S^{p+s_1,q+s_2,s_3}V \end{array}$$

Thus  $(A \otimes I)(\text{Ker}\pi) \subset \text{Ker}\pi$ . Observe that  $\text{Ker}\pi = \bigoplus_{(s_1,s_2,s_3) \in T} S^{p+s_1,q+s_2,s_3}V$ . Then we get the following commutative diagram:

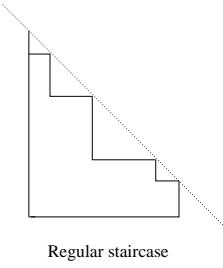
$$\begin{array}{ccc} \bigoplus_{(s_1,s_2,s_3) \in T} S^{p+s_1,q+s_2,s_3}V & \longrightarrow & S^{p,q}V \otimes S^sV \\ \downarrow & & \downarrow A \otimes I \\ \bigoplus_{(s_1,s_2,s_3) \in T} S^{p+s_1,q+s_2,s_3}V & \longrightarrow & S^{p,q}V \otimes S^sV \end{array}$$

Let  $W = V^\vee$ . Substitute  $W^\vee$  for  $V$  in the above diagram and dualize; the diagram we obtain is equivalent to the following commutative diagram of bundles on  $\mathbf{P}(W)$

$$\begin{array}{ccc} S^{p,q}W(-s) & \longrightarrow & \bigoplus_{(s_1,s_2,s_3) \in T} S^{p+s_1,q+s_2,s_3}W \\ A^\vee \downarrow & & \downarrow \\ S^{p,q}W(-s) & \longrightarrow & \bigoplus_{(s_1,s_2,s_3) \in T} S^{p+s_1,q+s_2,s_3}W \end{array}$$

By  $\mathcal{P}_T$  we conclude that  $A^\vee = \lambda I$  and then  $A = \lambda I$ .  $\square$

**Definition 39** We say that a staircase is **regular** if all the vertices of the steps (see Notation 33) are on a line with angular coefficient equal to  $-1$ .



**Lemma 40** The bundles whose support is a regular staircase are multistable.

*Proof.* Fact 1. For any regular staircase we have

$$\mu(H_i) > \mu(H_{i-1}) \quad \mu(E_i) > \mu(E_{i+1})$$

for any  $i$ , where  $H_i$  are the horizontal steps and  $E_i$  are the vertical steps (see Notation 33); recall that  $H_{i+1}$  is below  $H_i$  and  $E_{i+1}$  is on left of  $E_i$ .

**Proof.** Obviously it is sufficient to prove the statement for a regular staircase with two steps. It is a freshman calculation (even if a bit long) (use Lemma 28).  $\square$

Fact 2. Let  $S$  be a regular staircase. Then for every sticking out part  $O$  of  $S$  we have

$$\mu(O) > \mu(S - O)$$

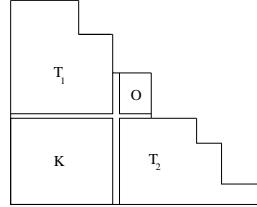
Therefore

$$\mu(S) > \mu(S - O)$$

**Proof.** Let  $b$  be the line on which the base of  $O$  is and let  $l$  be the line on which the left side of  $O$  is. Let  $T_1$  be the staircase whose vertices are the vertices of  $S$  that are either above  $b$  or on  $b$  and on the left of  $l$  (see the figure below). Let  $T_2$  be the staircase whose vertices are the vertices of  $S$  that are below  $b$  and either on the right of  $l$  or on  $l$ .

Let  $K$  be the rectangle

$$K = S - T_1 - T_2 - O$$



By Lemma 30  $\mu(O) > \mu(K)$ . Besides, by applying Fact 1 to the staircases  $T_1 + O$  and  $T_2 + O$  (where  $T_i + O$  is the smallest staircase containing  $T_i$  and  $O$ ), we get

$$\mu(O) > \mu(T_1) \quad \mu(O) > \mu(T_2)$$

Hence  $\mu(O) > \max\{\mu(K), \mu(T_1), \mu(T_2)\} \geq \mu(S - O)$  (see Remark 27).  $\square$

Now we are ready to prove that every bundle s.t. its  $\mathcal{Q}$ -support is a regular staircase  $S$  is multistable. Let  $C$  be the support of a  $\mathcal{Q}$ -representation subrepresentation of  $S$  (thus again a staircase by Remark 31). We want to prove  $\mu(C) < \mu(S)$  by induction on the number  $k$  of steps of  $C$ .

$k = 1$ . The statement follows from Lemma 30 and Fact 1.

$k - 1 \Rightarrow k$ . To prove this implication we do induction on

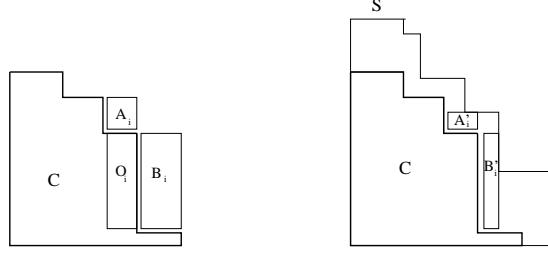
$$-\text{length}(\text{bd}(C) \cap \text{bd}(S))$$

where  $bd$  denotes the border and the border of a staircase is the border of the part of the plane inside the staircase.

Let  $C$  be a staircase with  $k$  steps support of a subrepresentation of  $S$ . Let  $O_i$  be the  $i$ -th sticking out part of  $C$ .

- If  $\mu(C - O_i) \geq \mu(C)$  for some  $i$  we conclude at once because  $C - O_i$  has  $k - 1$  steps; thus by induction assumption  $\mu(S) > \mu(C - O_i)$  and then  $\mu(S) > \mu(C)$ .
- Thus we can suppose  $\mu(C) > \mu(C - O_i) \forall i$  i.e.  $\mu(O_i) > \mu(C) \forall i$ .

Let  $A'_i$  be the biggest rectangle in  $A_i \cap S$  with the lower side equal to the lower side of  $A_i$  and let  $B'_i$  be the biggest rectangle in  $B_i \cap S$  with the left side equal to the left side of  $B_i$  (see Notation 33 for the definition of  $A_i$  and  $B_i$ ).



– Suppose  $\exists i$  s.t. either  $A'_i$  or  $B'_i$  is not empty; for instance suppose  $B'_i \neq \emptyset$ .

Since  $\mu(B'_i) > \mu(O_i)$  by Lemma 30 and  $\mu(O_i) > \mu(C)$  by assumption, we have  $\mu(B'_i) > \mu(C)$  and thus

$$\mu(C + B'_i) > \mu(C) \quad (8)$$

where  $C + B'_i$  is the smallest staircase containing  $C$  and  $B'_i$ . If  $B_i$  is a subgraph of  $S$  i.e.  $B_i = B'_i$ , then  $C + B'_i$  is a staircase with  $k - 1$  steps thus, by induction assumption,  $\mu(S) > \mu(C + B'_i)$ ; hence  $\mu(S) > \mu(C)$  by (8).

If  $B_i$  is not a subgraph of  $S$  i.e.  $B_i \neq B'_i$ , then  $\text{length}(bd(C + B'_i) \cap bd(S)) > \text{length}(bd(C) \cap bd(S))$  and by induction assumption  $\mu(S) > \mu(C + B'_i)$ ; hence we conclude again  $\mu(S) > \mu(C)$  by (8).

– If  $A'_i$  and  $B'_i$  are empty  $\forall i$  then there exists a chain of staircases  $C = S_0 \subset S_1 \subset \dots \subset S_r = S$  s.t.  $S_i$  is obtained from  $S_{i+1}$  taking off one of its sticking out parts, thus, by Fact 2, we conclude.  $\square$

**Lemma 41** a) The  $\mathcal{Q}$ -support of  $S^l Q(t) \otimes S^q V$  is (see also the figure below):

- i) if  $l \geq q$ , the subgraph of  $\mathcal{Q}$ , with all the multiplicities equal to 1, included in an isosceles right-angled triangle with horizontal and vertical catheti of length  $q$ , the direction of the hypotenuse equal to NW-SE, the vertex opposite to the hypotenuse equal to the lowest left vertex and equal to  $S^l Q(t - q)$
- ii) if  $l < q$  the subgraph of  $\mathcal{Q}$ , with all the multiplicities equal to 1, included in a right-angled trapezium with horizontal bases, left side orthogonal to the bases, right side with angular coefficient  $-1$ , length of the inferior base equal to  $q$ , the lowest left vertex equal to  $S^l Q(t - q)$ .

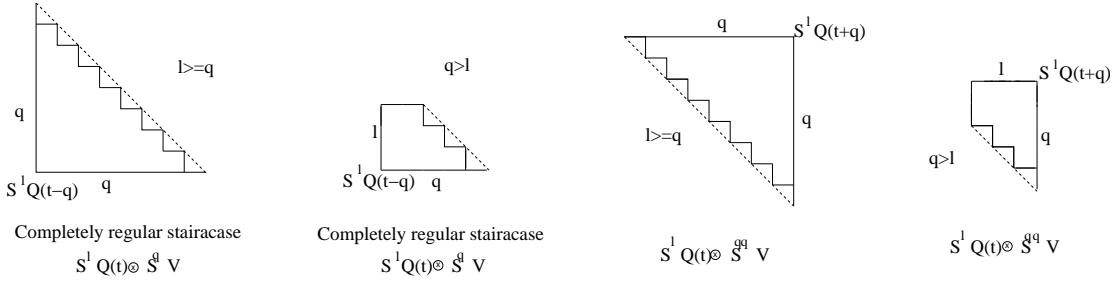
b) By duality (or directly) we can get an analogous statement for the  $\mathcal{Q}$ -support of  $S^l Q(t) \otimes S^{q,q} V$  (see the figure).

*Proof.* Use that  $S^q V = \bigoplus_{i=0, \dots, q} S^{q-i} Q(-i)$  as  $R$ -representation and Clebsch-Gordan's formula, see [F-H]: if  $l \geq m$

$$S^l Q(t) \otimes S^m Q(r) = S^{l+m} Q(t+r) \oplus S^{l+m-2} Q(t+r+1) \oplus \dots \oplus S^{l-m} Q(t+r+m)$$

□

**Definition 42** We say that a staircase is **completely regular** if it is equal to one of the subgraphs of  $\mathcal{Q}$  described in a Lemma 41.



**Lemma 43** A bundle whose support is a regular staircase is stable if and only if the staircase is not completely regular.

*Proof.* Observe that the  $\mathcal{Q}$ -support of  $S^l Q(t) \otimes S^{p,q} V$  has some multiplicity  $\geq 2$  if  $p \neq q$  and  $q \neq 0$ ; in fact among the vertices of the  $\mathcal{Q}$ -support of  $S^{p,q} V$  there are  $\mathcal{O}(2q-p)$  and  $S^2 Q(-1+2q-p)$ , thus, by Clebsch-Gordan's formula,  $S^l Q(t+2q-p)$  occurs at least twice in  $S^l Q(t) \otimes S^{p,q} V$ .

By Lemma 40 if a bundle  $E$  has a regular staircase as  $\mathcal{Q}$ -support, then  $E = E' \otimes T$  where  $E'$  is a stable vector bundle and  $T$  is a vector space  $SL(V)$ -representation; if  $T = S^{p,q} V$  with  $p \neq q$  and  $q \neq 0$  then by the previous remark the  $\mathcal{Q}$ -support of  $E' \otimes T$  has some multiplicity  $\geq 2$ . Thus we must have  $T = S^{q,q} V$  or  $T = S^q V$  and since the  $\mathcal{Q}$ -support of  $E' \otimes T$  is a staircase only the last case is possible by Lemma 41. Thus we conclude by Lemma 41, in fact a regular staircase can be the disjoint union of  $k$  completely regular staircases with the same length of the base if and only if  $k = 1$  i.e. it is a completely regular stairacase (we can see this arguing on the upper part of the border). □

**Remark 44** If  $p+q = p'+q'$ , then the rectangles that are the  $\mathcal{Q}$ -supports of  $S^{p,q} V(t)$  and  $S^{p',q'} V(t)$  have the highest right vertices on a line with angular coefficient  $-1$ . If  $p''+q''-t'' = p+q-t$  and  $t'' < t$ , then the highest right vertex of the  $\mathcal{Q}$ -support of  $S^{p'',q''} V(t'')$  is below this line.

**Lemma 45** Let  $p, q, s \in \mathbf{N}$  with  $p \geq q$  and  $s > 0$ .

Let  $T \subset \{(s_1, s_2, s_3) \mid s_1 + s_2 + s_3 = s, s_2 \leq p - q, s_3 \leq q\}$ ,  $T \not\ni (s, 0, 0)$ . Let  $A$  and  $B$  be two linear maps s.t. the following diagram of bundles on  $\mathbf{P}(V)$  commutes:

$$\begin{array}{ccc} S^{p,q}V(-s) & \xrightarrow{\varphi} & \bigoplus_{(s_1, s_2, s_3) \in T} S^{p+s_1, q+s_2, s_3}V \\ A \downarrow & & \downarrow B \\ S^{p,q}V(-s) & \xrightarrow{\varphi} & \bigoplus_{(s_1, s_2, s_3) \in T} S^{p+s_1, q+s_2, s_3}V \end{array}$$

where  $\varphi$  is an  $SL(V)$ -invariant map with all its components nonzero. Then  $A = \lambda I$  and  $B = \lambda I$  for some  $\lambda \in \mathbf{C}$ .

*Proof.* Observe that  $A(Ker(\varphi)) \subset Ker(\varphi)$ . Thus we have a commutative diagram

$$\begin{array}{ccc} Ker(\varphi) & \longrightarrow & S^{p,q}V(-s) \\ \downarrow A|_{Ker(\varphi)} & & \downarrow A \\ Ker(\varphi) & \longrightarrow & S^{p,q}V(-s) \end{array} \quad (9)$$

Let

$$0 \rightarrow R \rightarrow S \rightarrow Ker(\varphi) \rightarrow 0$$

be a minimal free resolution of  $Ker(\varphi)$ . By Lemma 14 the map  $A|_{Ker(\varphi)} : Ker(\varphi) \rightarrow Ker(\varphi)$  induces a commutative diagram

$$\begin{array}{ccccccc} 0 \rightarrow & R & \rightarrow & S & \rightarrow & Ker(\varphi) & \rightarrow 0 \\ & \downarrow & & \downarrow & & \downarrow A|_{Ker(\varphi)} & \\ 0 \rightarrow & R & \rightarrow & S & \rightarrow & Ker(\varphi) & \rightarrow 0 \end{array}$$

Let  $S_{max}$  be the direct sum of the summands of  $S$  with maximum twist and let  $S = S_{max} \oplus S'$ ; thus the previous diagram is

$$\begin{array}{ccccccc} 0 \rightarrow & R & \rightarrow & S_{max} & \oplus & S' & \rightarrow & Ker(\varphi) & \rightarrow 0 \\ & \downarrow & & \downarrow & \swarrow & \downarrow & & \downarrow A|_{Ker(\varphi)} & \\ 0 \rightarrow & R & \rightarrow & S_{max} & \oplus & S' & \rightarrow & Ker(\varphi) & \rightarrow 0 \end{array}$$

Then we get a commutative diagram

$$\begin{array}{ccc} S_{max} & \rightarrow & Ker(\varphi) \\ \downarrow \alpha & & \downarrow A|_{Ker(\varphi)} \\ S_{max} & \rightarrow & Ker(\varphi) \end{array}$$

and, if  $f$  is the composition of the map  $S_{max} \rightarrow Ker(\varphi)$  with the inclusion  $Ker(\varphi) \rightarrow S^{p,q}V(-s)$ , by (9) we get the commutative diagram

$$\begin{array}{ccc} S_{max} & \xrightarrow{f} & S^{p,q}V(-s) \\ \downarrow \alpha & & \downarrow A \\ S_{max} & \xrightarrow{f} & S^{p,q}V(-s) \end{array} \quad (10)$$

and thus a commutative diagram

$$\begin{array}{ccccccc} 0 \rightarrow & Ker(f) & \rightarrow & S_{max} & \xrightarrow{f} & Im(f) & \rightarrow 0 \\ & & & \downarrow \alpha & & \downarrow \gamma & \\ 0 \rightarrow & Ker(f) & \rightarrow & S_{max} & \xrightarrow{f} & Im(f) & \rightarrow 0 \end{array} \quad (11)$$

where  $\gamma = A|_{Im(f)}$ .

Now we will prove that if  $Im(f)$  is simple then  $A$  is a multiple of the identity.

Let  $0 \rightarrow K \rightarrow M \rightarrow (Imf)^\vee \rightarrow 0$  be a minimal free resolution of  $(Imf)^\vee$ ; for any  $\beta : M \rightarrow M$  induced by  $\gamma^\vee$  we have the following commutative diagram:

$$\begin{array}{ccc} M & \rightarrow & (Imf)^\vee \\ \downarrow \beta & & \downarrow \gamma^\vee \\ M & \rightarrow & (Imf)^\vee \end{array}$$

and then by (11)

$$\begin{array}{ccc} M & \xrightarrow{r} & S_{max}^\vee \\ \downarrow \beta & & \downarrow \alpha^\vee \\ M & \xrightarrow{r} & S_{max}^\vee \end{array}$$

In particular, since  $(Imf)^\vee$  is simple,  $\gamma^\vee$  is a multiple of the identity, thus  $\beta$  can be taken equal to a multiple of the identity.

Observe that all the components of  $r$  are nonzero (because the map  $M \rightarrow (Imf)^\vee$  is surjective and all the components of  $f^\vee : (Imf)^\vee \rightarrow S_{max}^\vee$  are nonzero, since no component of  $S_{max}$  is sent to 0 by  $f$ ); besides, up to twisting, we can suppose  $S_{max}$  is a trivial bundle and then  $H^0(r^\vee)^\vee$  is a projection. Hence, since  $\beta$  is a multiple of the identity,  $\alpha^\vee$  (and then  $\alpha$ ) is a multiple of the identity.

Thus, by (10) also  $A$  is a multiple of the identity as we wanted (twist (10) by  $s$  and consider  $H^0(\cdot)^\vee$  of every map of the obtained diagram; in this way we get a diagram of  $SL(V)$ -representations whose horizontal maps are surjective, since they are  $SL(V)$ -invariant and nonzero and  $S^{p,q}V$  is irreducible).

Observe that, by Remark 44, the  $\mathcal{Q}$ -support of  $Imf$  is a regular staircase in the  $\mathcal{Q}$ -support of  $S^{p,q}V(-s)$ , since all the summands of  $S_{max}$  have the same twist.

Thus by Lemma 43 we can conclude at once if the  $\mathcal{Q}$ -support of  $Imf$  is not a completely regular staircase.

Therefore we can suppose the  $\mathcal{Q}$ -support of  $Imf$  is a completely regular staircase.

Observe that, by Remark 44, if the  $\mathcal{Q}$ -support  $Imf$  is a completely regular staircase then  $S = S_{max}$  and thus  $Imf = Ker\varphi$ .

Consider the following exact sequence

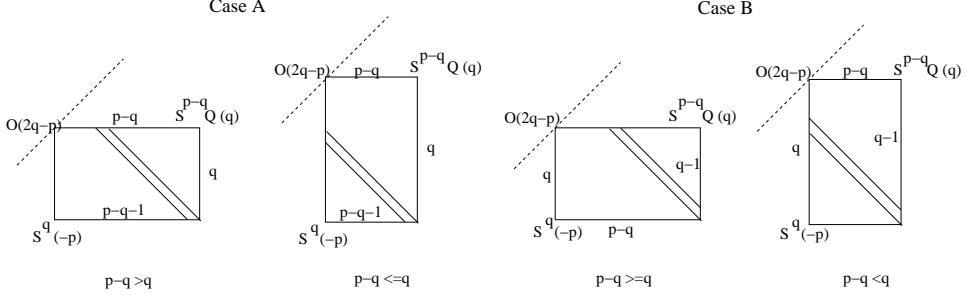
$$0 \rightarrow Ker\varphi \rightarrow S^{p,q}V(-s) \rightarrow Im\varphi \rightarrow 0 \tag{12}$$

Up to dualizing we can suppose that also the  $\mathcal{Q}$ -support of  $Im\varphi$  is of the kind  $b$  of Lemma 41.

Thus the unique remaining cases are the cases in which the sequence (12) twisted by  $s$  is one of the following:

$$Case A \quad 0 \rightarrow S^qQ(-q-1) \otimes S^{p-q-1}V \rightarrow S^{p,q}V \rightarrow S^{p-q}Q \otimes S^{q,q}V \rightarrow 0$$

$$Case B \quad 0 \rightarrow S^qQ(-q) \otimes S^{p-q}V \rightarrow S^{p,q}V \rightarrow S^{p-q}Q(1) \otimes S^{q-1,q-1}V \rightarrow 0$$



Observe that the Case B is equivalent to Case A (by dualizing and considering  $q' = p - q$ ). Thus it is sufficient to consider Case A. By (9) we get a commutative diagram

$$\begin{array}{ccccccc}
 0 \rightarrow & S^q Q(-q-1) \otimes S^{p-q-1} V & \rightarrow & S^{p,q} V & \rightarrow & S^{p-q} Q \otimes S^{q,q} V & \rightarrow 0 \\
 & \downarrow & & \downarrow & & \downarrow & \\
 0 \rightarrow & S^q Q(-q-1) \otimes S^{p-q-1} V & \rightarrow & S^{p,q} V & \rightarrow & S^{p-q} Q \otimes S^{q,q} V & \rightarrow 0
 \end{array}$$

By taking the cohomology (in particular  $H^0$ ) we get

$$\begin{array}{ccccccc}
 0 & \rightarrow & 0 & \rightarrow & S^{p,q} V & \rightarrow & S^{q,q} V \otimes S^{p-q} V \\
 \downarrow & & \downarrow & & \downarrow & & \\
 0 & \rightarrow & 0 & \rightarrow & S^{p,q} V & \rightarrow & S^{q,q} V \otimes S^{p-q} V
 \end{array}$$

since  $H^0(S^q Q(-q-1)) = 0$  and  $H^0(S^{p-q} Q) = S^{p-q} V$  (to calculate the cohomology of  $S^l Q(t)$  use for instance its minimal resolution  $0 \rightarrow S^{l-1} V(t-1) \rightarrow S^l V(t) \rightarrow S^l Q(t) \rightarrow 0$ ). We conclude by applying Lemma 37 to the dual of the right part of the diagram.  $\square$

From Lemmas 45 and 38 we deduce at once:

**Corollary 46** *Let  $p, q, s \in \mathbf{N}$  with  $p \geq q$ . Let  $A$  and  $B$  be two linear maps s.t. the following diagram of bundles on  $\mathbf{P}(V)$  commutes:*

$$\begin{array}{ccc}
 S^{p,q} V(-s) & \xrightarrow{\varphi} & W \\
 A \otimes I \downarrow & & \downarrow B \\
 S^{p,q} V(-s) & \xrightarrow{\varphi} & W
 \end{array}$$

where  $W$  is a non trivial  $SL(V)$ -submodule of  $S^{p,q} V \otimes S^s V$  and all the components of  $\varphi$  are nonzero  $SL(V)$ -invariant maps. Then  $A = \lambda I$  and  $B = \lambda I$  for some  $\lambda \in \mathbf{C}$ .

*Proof of Theorem 3.* The case  $p = 0$  is trivial. Thus we can suppose  $p > 0$ . By Corollary 46, the only thing we have to prove is that if in  $W \otimes \mathcal{O}$  there are two copies of an irreducible bundle  $F$ , i.e.  $W = F \oplus F \oplus W'$ , then  $E$  is not simple: in fact the following diagram induces an automorphism on  $E$  not multiple of the identity:

$$\begin{array}{ccccccccc}
 0 \rightarrow & S^{p,q} V(-s) & \rightarrow & F & \oplus & F & \oplus & W' & \rightarrow E \rightarrow 0 \\
 & \downarrow I & & -I \downarrow & \swarrow 2I & \downarrow I & \downarrow I & & \downarrow \\
 0 \rightarrow & S^{p,q} V(-s) & \rightarrow & F & \oplus & F & \oplus & W' & \rightarrow E \rightarrow 0
 \end{array}$$

(see Lemma 14).  $\square$

The following theorem gives a precise criterion to see when a regular elementary homogeneous bundle  $E$  on  $\mathbf{P}^2$  is stable or simple in the case the difference of the twists of the first bundle and of the middle bundle of the minimal free resolution of  $E$  is 1.

**Theorem 47** *Let  $E$  be a homogeneous bundle on  $\mathbf{P}^2$  with minimal free resolution*

$$0 \rightarrow S^{p,q}V \xrightarrow{\varphi} \bigoplus_{\alpha \in \mathcal{A}} S^{p+s_1^\alpha, q+s_2^\alpha, s_3^\alpha} V(1) \rightarrow E \rightarrow 0$$

with  $p \geq q \geq 0$ ,  $s_i^\alpha \in \mathbf{N}$ ,  $1 = s_1^\alpha + s_2^\alpha + s_3^\alpha$ ,  $\mathcal{A}$  finite subset of indices and all the components of  $\varphi$  nonzero  $SL(V)$ -invariant maps. Then

(i)  $E$  is simple if and only if its minimal free resolution has one of the following forms:

$$0 \rightarrow S^{p,q}V \rightarrow S^{p+1,q}V(1) \rightarrow E \rightarrow 0$$

$$0 \rightarrow S^{p,q}V \rightarrow S^{p+1,q}V(1) \oplus S^{p,q+1}V(1) \rightarrow E \rightarrow 0$$

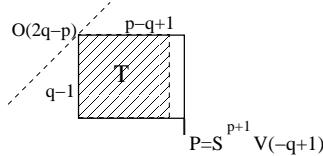
with  $q \neq 0$ ,

$$0 \rightarrow S^{p,q}V \rightarrow S^{p+1,q}V(1) \oplus S^{p,q+1}V(1) \rightarrow E \rightarrow 0$$

with  $q \neq 0$  and  $p \neq q$ .

(ii)  $E$  is stable if and only if  $E$  is simple and, moreover, in the case its minimal resolution is of the third type  $2q \geq p > q$ .

*Proof* (i) follows from Theorem 3. So it is enough to check when the bundles described in (i) are stable. The first case follows from Lemma 37. For the second case note that the  $\mathcal{Q}$ -support of  $E$  is a not completely regular staircase, thus we conclude by Lemma 43. In the third case the  $\mathcal{Q}$ -support of  $E$  is the following:



The bundle  $E$  is multistable if and only if  $\mu(T) < \mu(E)$  and  $\mu(P) < \mu(E)$  and, by using Lemma 28, one can show that this is true if and only if  $-5p + 2q - 2 - 4p^2 + 3pq + p^2q - p^3 < 0$  and  $3p^2 + p^3 - 8pq - 2p^2q - 4 - 8q < 0$  respectively. The first inequality always holds since  $p \geq q$ . The last inequality is equivalent to  $p \leq 2q$  since its first member is equal to  $(p+2)^2(p-1-2q)$ . Thus  $E$  is multistable if and only if  $p \leq 2q$ . In this case, by Lemma 41, it is stable if and only if  $p \neq q$ .  $\square$

In [Fa] an example of a simple unstable homogeneous bundle on  $\mathbf{P}^2$  is exhibited. Theorem 47 shows infinite examples of such bundles.

We end with a theorem which studies the simplicity of elementary homogeneous bundles.

**Theorem 48** Let  $p \geq q$ . Let  $E$  be the homogeneous vector bundle on  $\mathbf{P}^2 = \mathbf{P}(V)$  defined by the following exact sequence ( $\mathcal{A}$  a finite set of indices):

$$0 \rightarrow S^{p,q}V \xrightarrow{\varphi} \bigoplus_{\alpha \in \mathcal{A}} S^{p+s_1^\alpha, q+s_2^\alpha, s_3^\alpha} V(s^\alpha) \rightarrow E \rightarrow 0$$

where the components  $\varphi_\alpha$  of  $\varphi$  are  $SL(V)$ -invariant maps and  $s_1^\alpha + s_2^\alpha + s_3^\alpha = s^\alpha \forall \alpha \in \mathcal{A}$ . Then  $E$  is simple if and only if the following five conditions hold:

- a)  $\exists \alpha, \beta \in \mathcal{A}$  s.t.  $s_i^\alpha \leq s_i^\beta$   $i = 1, 2, 3$
- b) all the components  $\varphi_\alpha$  of  $\varphi$  are nonzero, in particular  $p \geq q + s_2^\alpha$  and  $q \geq s_3^\alpha \forall \alpha \in \mathcal{A}$
- c)  $\forall \alpha, \beta \in \mathcal{A}$  s.t.  $s^\alpha > s^\beta$ , we have that if  $s_2^\beta > 0$  then  $s_3^\beta + s^\alpha - s^\beta < q + 1$  and if  $s_1^\beta > 0$  then  $q + s_2^\beta + s^\alpha - s^\beta < p + 1$
- d)  $\forall \alpha, \beta, \gamma \in \mathcal{A}$  s.t.  $s^\alpha = s^\beta < s^\gamma$ , we have  $s^\gamma - s^\alpha \geq \max\{|s_i^\alpha - s_i^\beta| \mid i = 1, 2, 3\}$
- e) if  $p > 0$  and  $\exists s$  s.t.  $s^\alpha = s \forall \alpha \in \mathcal{A}$  then  $\bigoplus_{\alpha \in \mathcal{A}} S^{p+s_1^\alpha, q+s_2^\alpha, s_3^\alpha} V \neq S^{p,q}V \otimes S^s V$ .

*Sketch of the proof.* Any automorphism  $\eta$  of  $E$  induces maps  $A$  and  $B$  as in Lemma 14 and given  $A$  and  $B$  we have an automorphism of  $E$ .

We call  $B_{\mathcal{K}, \mathcal{J}} : \bigoplus_{\alpha \in \mathcal{J}} S^{p+s_1^\alpha, q+s_2^\alpha, s_3^\alpha} V(s^\alpha) \rightarrow \bigoplus_{\alpha \in \mathcal{K}} S^{p+s_1^\alpha, q+s_2^\alpha, s_3^\alpha} V(s^\alpha)$  the map induced by  $B$ ,  $\forall \mathcal{J}, \mathcal{K}$  of  $\mathcal{A}$ . We denote  $B_J = B_{J, J}$ ,  $B_{\alpha, \beta} = B_{\{\alpha\}, \{\beta\}}$  and  $B_\alpha = B_{\{\alpha\}}$  for short. Besides  $\varphi_{\mathcal{J}} : S^{p,q}V \rightarrow \bigoplus_{\alpha \in \mathcal{J}} S^{p+s_1^\alpha, q+s_2^\alpha, s_3^\alpha} V(s^\alpha)$  denotes the map induced by  $\varphi$ ,  $\forall \mathcal{J} \subset \mathcal{A}$ .

We show now that the simplicity of  $E$  implies  $a, b, c, d, e$ ;  $a, b$  and  $e$  are left to the reader.

- c) Observe that if for some  $\bar{\alpha}, \bar{\beta} \in \mathcal{A}$  there exists a nonzero map

$$\gamma : S^{p+s_1^{\bar{\beta}}, q+s_2^{\bar{\beta}}, s_3^{\bar{\beta}}} V(s^{\bar{\beta}}) \rightarrow S^{p+s_1^{\bar{\alpha}}, q+s_2^{\bar{\alpha}}, s_3^{\bar{\alpha}}} V(s^{\bar{\alpha}})$$

s.t.  $\gamma \circ \varphi_{\bar{\beta}} = 0$  then  $E$  is not simple (take  $B_{\bar{\alpha}, \bar{\beta}} = \gamma$ ,  $A = I$ ,  $B_\alpha = I \forall \alpha \in \mathcal{A}$ ,  $B_{\alpha, \beta} = 0 \forall (\alpha, \beta) \neq (\bar{\alpha}, \bar{\beta})$  and use Lemma 14). Such a  $\gamma$  exists if and only if there exists a nonzero map

$$\Gamma : S^{p+s_1^\beta, q+s_2^\beta, s_3^\beta} V \otimes S^{s^{\bar{\alpha}} - s^\beta} V \rightarrow S^{p+s_1^{\bar{\alpha}}, q+s_2^{\bar{\alpha}}, s_3^{\bar{\alpha}}} V$$

s.t.  $\Gamma \circ H^0((\varphi_\beta(-s^{\bar{\alpha}}))^\vee)^\vee = 0$  This is equivalent to the non surjectivity of  $H^0((\varphi_\beta(-s^{\bar{\alpha}}))^\vee)^\vee$  (which is the injection followed by the projection  $S^{p,q}V \otimes S^{s^{\bar{\alpha}}} V \rightarrow S^{p,q}V \otimes S^{s^\beta} V \otimes S^{s^{\bar{\alpha}} - s^\beta} V \rightarrow S^{p+s_1^\beta, q+s_2^\beta, s_3^\beta} V \otimes S^{s^{\bar{\alpha}} - s^\beta} V$ ) and we conclude by Pieri's formula.

- d) Obviously if for some  $\alpha, \beta, \gamma \in \mathcal{A}$  s.t.  $s^\alpha = s^\beta < s^\gamma$  there exist nonzero maps

$$\begin{aligned} \delta &: S^{p+s_1^\alpha, q+s_2^\alpha, s_3^\alpha} V(s^\alpha) \rightarrow S^{p+s_1^\gamma, q+s_2^\gamma, s_3^\gamma} V(s^\gamma) \\ \delta' &: S^{p+s_1^\beta, q+s_2^\beta, s_3^\beta} V(s^\beta) \rightarrow S^{p+s_1^\gamma, q+s_2^\gamma, s_3^\gamma} V(s^\gamma) \end{aligned}$$

s.t.  $\delta \circ \varphi_\alpha + \delta' \circ \varphi_\beta = 0$  then  $E$  is not simple (take  $A = I$ ,  $B_\alpha = I \forall \alpha \in \mathcal{A}$ ,  $B_{\gamma, \alpha} = \delta$ ,  $B_{\beta, \alpha} = \delta'$  and  $B_{\epsilon, \lambda} = 0 \forall (\epsilon, \lambda) \neq (\gamma, \alpha), (\gamma, \beta)$ ). Such  $\delta$  and  $\delta'$  exist if and only if

$$S^{p,q}V \otimes S^{s^\gamma} V \xrightarrow{H^0(\varphi_\alpha(-s^\gamma))^\vee \times H^0(\varphi_\beta(-s^\gamma))^\vee} (S^{p+s_1^\alpha, q+s_2^\alpha, s_3^\alpha} V \otimes S^{s^\gamma - s^\alpha} V) \oplus (S^{p+s_1^\beta, q+s_2^\beta, s_3^\beta} V \otimes S^{s^\gamma - s^\beta} V)$$

is not surjective; since  $H^0(\varphi_\alpha(-s^\gamma)^\vee)^\vee$  and  $H^0(\varphi_\beta(-s^\gamma)^\vee)^\vee$  are surjective by  $c$ , this is true if and only if  $S^{p+s_1^\alpha, q+s_2^\alpha, s_3^\alpha} V \otimes S^{s^\gamma-s^\alpha} V$  and  $S^{p+s_1^\beta, q+s_2^\beta, s_3^\beta} V \otimes S^{s^\gamma-s^\alpha} V$  have a nonzero subrepresentation in common and we conclude.

Suppose now  $a, b, c, d, e$  hold. We may assume  $p > 0$ . Let  $\eta$  be an automorphism of  $E$  and let  $B$  and  $A$  be the induced maps as above.

Let  $\mathcal{A} = \mathcal{A}' \cup \mathcal{A}'' \cup \dots$  be disjoint union s.t.  $\mathcal{A}'$  is the set of indices  $\alpha$  in  $\mathcal{A}$  s.t.  $s_\alpha$  is the minimum of  $\{s_\alpha \mid \alpha \in \mathcal{A}\}$ ,  $\mathcal{A}''$  is the set of indices  $\alpha$  in  $\mathcal{A} - \mathcal{A}'$  s.t.  $s_\alpha$  is the minimum of  $\{s_\alpha \mid \alpha \in \mathcal{A} - \mathcal{A}'\}$  and so on. Let  $s' = s^\alpha$  for  $\alpha \in \mathcal{A}'$  and  $s'' = s^\alpha$  for  $\alpha \in \mathcal{A}''$  and so on.

We have  $\varphi_{\mathcal{A}'} \circ A = B_{\mathcal{A}'} \circ \varphi_{\mathcal{A}'}$ ; thus, by Corollary 46,  $A = \lambda I$  and  $B_{\mathcal{A}'} = \lambda I$ .

Besides we have

$$\varphi_{\mathcal{A}''} \circ A = B_{\mathcal{A}''} \circ \varphi_{\mathcal{A}''} + B_{\mathcal{A}'', \mathcal{A}'} \circ \varphi_{\mathcal{A}'}$$

thus we get  $(\lambda I - B_{\mathcal{A}''}) \circ \varphi_{\mathcal{A}''} = B_{\mathcal{A}'', \mathcal{A}'} \circ \varphi_{\mathcal{A}'}$ . By applying  $H^0(\cdot^\vee)^\vee$ , we obtain

$$\begin{array}{ccc} S^{p, q} V \otimes S^{s''} V & \xrightarrow{H^0(\varphi_{\mathcal{A}''}^\vee)^\vee} & \bigoplus_{\alpha \in \mathcal{A}''} S^{p+s_1^\alpha, q+s_2^\alpha, s_3^\alpha} V \\ H^0(\varphi_{\mathcal{A}'}^\vee)^\vee \downarrow & & \downarrow H^0((\lambda I - B_{\mathcal{A}''})^\vee)^\vee \\ \bigoplus_{\alpha \in \mathcal{A}'} S^{p+s_1^\alpha, q+s_2^\alpha, s_3^\alpha} V \otimes S^{s''-s'} V & \xrightarrow{H^0(B_{\mathcal{A}'', \mathcal{A}'}^\vee)^\vee} & \bigoplus_{\alpha \in \mathcal{A}''} S^{p+s_1^\alpha, q+s_2^\alpha, s_3^\alpha} V \end{array}$$

By  $a$  we have that  $\bigoplus_{\alpha \in \mathcal{A}''} S^{p+s_1^\alpha, q+s_2^\alpha, s_3^\alpha} V$  is in the kernel of the map

$$H^0(\varphi_{\mathcal{A}'}^\vee)^\vee : S^{p, q} V \otimes S^{s''} V \rightarrow \bigoplus_{\alpha \in \mathcal{A}'} S^{p+s_1^\alpha, q+s_2^\alpha, s_3^\alpha} V \otimes S^{s''-s'} V$$

thus  $\lambda I - B_{\mathcal{A}''} = 0$ , then  $B_{\mathcal{A}''} = \lambda I$  and  $B_{\mathcal{A}'', \mathcal{A}'} \circ \varphi_{\mathcal{A}'} = 0$ . Hence by  $c$  and  $d$  we get  $B_{\mathcal{A}'', \mathcal{A}'} = 0$  (arguing as in the proof of the other implication).

By induction on the number of the subsets  $\mathcal{A}', \mathcal{A}''$ , ... we conclude.  $\square$

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